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*Computer-Aided Structural Engineering (CASE) Project*

# Procedure for Static Analysis of Gravity Dams Including Foundation Effects Using the Finite Element Method – Phase 1B

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Final report



**Prepared for** U.S. Army Corps of Engineers
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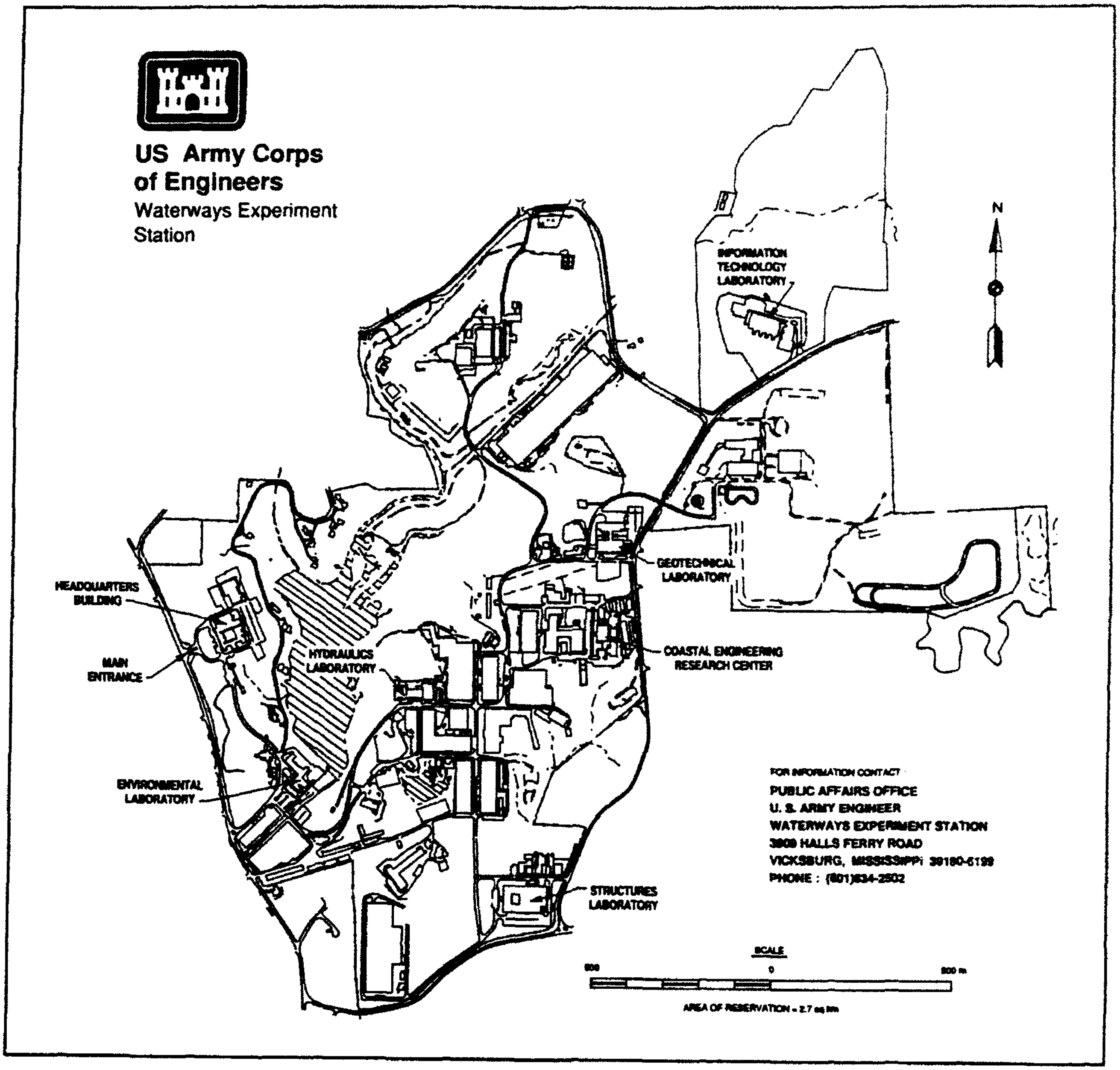



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# Contents

# Preface

This report is aimed at providing information for the use of the finite element method of analysis for the analysis of concrete gravity dams. The Phase Ia report will address only the static analysis of the gravity dam, while this Phase Ib report will address the effect of the foundation in the static analysis of concrete gravity dams. The Phase II report addressed the dynamic analysis of concrete gravity dams. The work was sponsored under funds provided to the U.S. Army Engineer Waterways Experiment Station (WES) by the Engineering Division of Headquarters of the U.S. Army Corps of Engineers (HQUSACE) as part of the Computer-Aided Structural Engineering (CASE) Project. Mr. Lucian Guthrie of the Structures Branch of the Engineering Division was the HQUSACE point of contact.

Input for the report was obtained from the CASE Task Group on Finite Element Analysis. Members and others who directly contributed to the report were:

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The report was compiled and written by Mr. Jerry Foster and Mr. H. Wayne Jones. The work was managed, coordinated, and monitored in the Information Technology Laboratory (ITL), WES, by Mr. Jones, Computer-Aided Engineering Division (CAED), under the general supervision of Dr. N. Radhakrishnan, Director, ITL.

At the time of the publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

# Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

| Multiply | By | To Obtain |
|---|---|---|
| degrees (angle) | 0.01745329 | radians |
| feet | 0.3048 | meters |
| inches | 2.54 | centimeters |
| pounds (force) per square inch | 6.894757 | kilopascals |
| pounds (mass) per cubic foot | 16.01846 | kilograms per cubic meter |

# 1 Introduction

## Purpose

The structural engineer has long been faced with the question of what effect does the foundation have on the structure and when should the foundation be included in the analysis of the structure. If it is necessary to include the foundation, similar questions arise as to what model should be used for the foundation and how much of the foundation is necessary. The objectives of this study are to determine the impact of foundation-structure interaction upon stresses within a gravity dam and to make recommendations concerning how and when to include the foundation in a finite element analysis.

This study is part of the continuing effort of the Computer-Aided Structural Engineering (CASE) Committee, Finite Element Task Group, to establish guidelines for the analysis of gravity dams using the finite element method. Previous work by the Task Group has been utilized within this study and is referenced where used. All of the analyses within this report use linear elastic models of the structure and foundation. Analyses using nonlinear foundation behavior will be examined in a later study.

## Approach

Several numerical models for the foundation were examined and are summarized in Chapter 2 with recommendations on strengths and limitations of each. A finite element model of the foundation is selected from these models for use in the remainder of this study.

The foundation size required to obtain stress convergence within the foundation based on a uniformly applied loading is investigated in Chapter 3. The effect of the foundation on the stresses inside the structure is investigated in Chapter 4 by varying the size of the finite element foundation model while maintaining a constant finite element model for the gravity dam. The stresses within the dam are examined to determine what conclusions can be drawn concerning stress convergence as the foundation size is varied. In Chapter 5, one finite element model of the foundation is selected, based on stress convergence, to study the impact upon the stresses in the dam for various ratios of foundation-to-dam elastic moduli.

# 2 Foundation Models to be Used for Finite Element Structures

## Foundation Models

The finite element method (FEM) is a common method for determining the displacements and stresses within complex structures. The effects of the foundation often contribute an important part to the behavior of many structures and must be considered. However, the structural engineer may not be interested in the behavior within the foundation except to the extent that the structure and foundation interact and influence the behavior within the structure. Many models for the foundation are available to the engineer with the following being the most frequently used types:

*a*. Winkler Foundation.

*b*. Two-Parameter Foundation.

*c*. Boundary Element Method.

*d*. Elastic Half-Plane.

*e*. Finite Element Method.

This chapter gives a brief summary of these foundation models, along with the limitations and strengths of each.

## Winkler Foundation

The Winkler foundation is based on Winkler's (1867) hypothesis: the displacement of a single point on the foundation is independent of the displacements at any other point on the foundation and is a function of the stiffness of the foundation at that point. This model allows the foundation to be described as a series of one-dimensional (1-D) springs which can be coupled numerically with the structure stiffness as shown below:

$$\left[K_T\right]\{u\} = \{F\} \tag{1}$$

where

$[K_T] = [K_S] + [K_F]$

$[K_F]$ = stiffness matrix of Winkler foundation (diagonal matrix)

$[K_S]$ = stiffness matrix of structure

$[K_T]$ = stiffness matrix of coupled foundation-structure system

$\{u\}$ = displacements of system nodes

$\{F\}$ = forces acting on system

This procedure has been used to solve many soil-structure interaction problems (Dawkins 1982, Haliburton 1971, Reese and Matlock 1956). The basic weakness of this foundation model is that it does not give a coupled two-dimensional (2-D) representation of the foundation. This weakness can be demonstrated by placing a uniform load on a uniform beam which rests on a Winkler foundation. With a Winkler foundation model this analysis yields a constant displacement of the beam, i.e., rigid body deflection. Since all of the relative displacements within the beam are zero, all moments and shears within the beam are zero. This foundation model would not model the true behavior of such a problem. The stiffness matrix, $[K_T]$, given in Equation 1 is a function of the material and geometric properties of the foundation and structure, which makes an assumption of an overall stiffness of the foundation stiffness necessary. There is literature which contains tables with ranges of modulus values for the foundation, or they may be determined empirically. The Winkler foundation model should be used with extreme care keeping these limitations in mind.

## Two-Parameter Model

Nogami and Lam (1986) developed a two-parameter model for analyzing a beam resting on the ground surface. The two parameters represent a vertical stiffness and a shearing stiffness. These two parameters give the 2-D coupling within the foundation not present in the Winkler model. Prior to Nogami, other two-parameter models for the soil-structure interaction (SSI) analysis were determined by known ground surface displacements or by using a variational method with an assumed ground surface displacement. Since the ground surface displacements are needed for these models, the two parameters for these models are difficult to determine. The two parameters used in Nogami's model are calculated from Young's modulus ($E$) and Poisson's ratio ($\nu$) of the foundation. Therefore, they are easy to determine once $E$ and $\nu$ are known.

The following is a brief outline of Nogami's two-parameter model. A linearly elastic 2-D foundation can be represented with the following two-parameter model:

$$p(x,y) = Kw(x,y) - G\nabla^2 w(x,y) \tag{2}$$

where

$$\nabla^2 = \left(\frac{\partial}{\partial x^2} + \frac{\partial}{\partial y^2}\right)$$

$$p = \text{pressure}$$

$$K, G = \text{soil parameters}$$

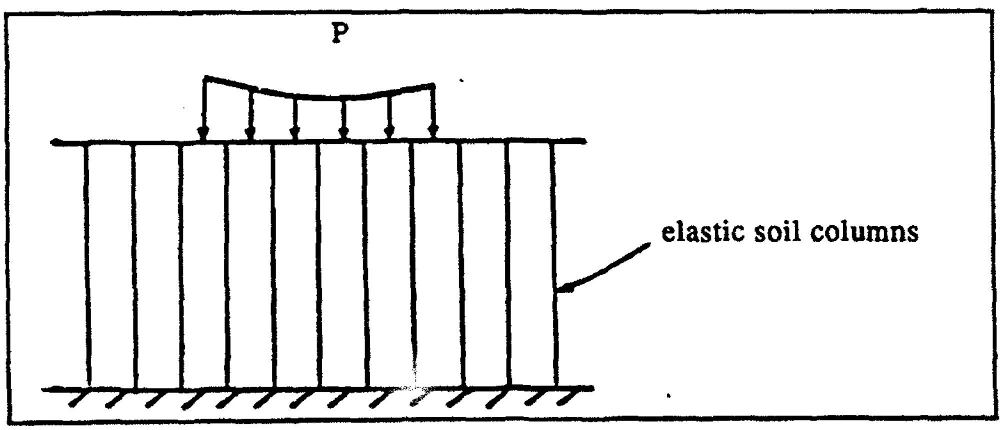
$$w = \text{displacements}$$

Nogami discretized the ground surface and used variational methods to arrive at the following equation:

$$[K]\{w(x)\} - [N]\{\nabla^2 w(x)\} = \{p(x)\} \tag{3}$$

where $[N]$ and $[K]$ are n by n matrices, and $w(x)$ represents the vertical displacements at the interface between the foundation and structure.

As seen in Equation 3, the effect of the foundation is represented by only the displacements at the ground surface. This representation is accomplished by assuming the entire foundation is made up of a series of elastic soil columns as illustrated below. The stresses in the foundation can then be described by the following equations:




Soil media idealized by a system of elastic columns

Axial normal stress:

$$\sigma(x,y) = E\,\frac{\partial w(x,y)}{\partial y}$$

Shear stress along sides:

$$\tau(x,y) = G\,\frac{\partial w(x,y)}{\partial x}$$

where

$$w(x,y) = \sum_{i=1} \varphi_i(y) w_i$$

The $\varphi_i$ function is an assumed linear shape function. From these equations the stresses anywhere in the foundation can be determined if the surface displacements are known. The equation for a plate resting on a foundation is as follows:

$$[EI]\left\{\frac{\partial^3 w(x)}{\partial x^3}\right\} - [N]\left\{\frac{\partial^2 w(x)}{\partial x^2}\right\} + [K]\{w(x)\} = \{p(x)\}$$

For a continuous media model consisting of elastic columns with completely restrained lateral displacements, the stress can be written as follows:

$$\sigma(x,y) = A\,\frac{\partial w(x,y)}{\partial x}$$

$$\tau(x,y) = B\,\frac{\partial w(x,y)}{\partial x}$$

where

$$A = \frac{(1 - \nu_s)\,E_s}{2(1 + \nu_s)\,(1 - \nu_s)}$$

$$B = \frac{E_s}{2(1 + \nu_s)}$$

$E_s$ = Young's modulus for soil

$\nu_s$ = Poisson's ratio for soil

However, if the elastic columns are not completely restrained, the stress equation can be approximated by the following:

$$\sigma(x,y) = F_e A \frac{\partial w(x,y)}{\partial y} \tag{4}$$

$$\tau(x,y) = F_a B \frac{\partial w(x,y)}{\partial x}$$

From finite element studies, the relationships were determined for $F_e$ and $F_a$ as a function of $\nu_s$. The following are limits for $\nu_s$ values between 0.0 and 0.3 for $F_e$ and $F_a$:

| | | |
|---|---|---|
| $\nu_s$ | 0.0 | 0.3 |
| $F_e$ | 0.95 | 0.99 |
| $F_a$ | 0.475 | 0.495 |

Graphs for $F_e$ and $F_a$ as a function of $\nu_s$ are presented by Nogami and Lam (1986).

Therefore by determining the Young's modulus and Poisson's ratio of the foundation, an engineer can find the corresponding $F_e$ and $F_a$. Using these values and applying the proper boundary conditions, the engineer can solve Equation 4 to determine the displacements in the structure which leads directly to the determination of the shear and moments. The major problem with this foundation model is that it can not be used to produce a stiffness matrix for the foundation to be later combined with the structure stiffness matrix.

## Boundary Element Method

The boundary element method (BEM) is a numerical analysis procedure which has an advantage over the FEM for many problems since only the boundary must be discretized, not the interior of the system as in the FEM. The value of using BEM instead of FEM has decreased in recent years because of the increase in computational capacity available on computers today. The need for decreasing the number of elements used in an analysis is not as critical as it was when the BEM was developed.

The BEM and its application to soil-structure interaction problems has been discussed by Vallabhan and Sivakumar (1986). Vallabhan and Sivakumar developed a procedure to combine a boundary element model of the foundation with a finite element model of the structure. This boundary element foundation was numerically constructed using linear elements. The structure was modeled by linearly elastic 2-D isoparametric plate finite elements.

The BEM is typically stated as follows:

$$[H]\{\varphi\} = [G]\{q\}$$

For an elastic half-plane problem:

$\{\varphi\}$ = nodal displacements

$\{q\}$ = surface tractions

$[H], [G]$ = n by n matrices

$n$ = number of degrees of freedom

Since these matrices represent a well-posed boundary value problem, only the traction or displacement can be described at any given node. Therefore, the set of equations can be reordered as follows:

$$[A]\{X\} = \{B\}$$

where

$[A]$ = combination of $[H]$ and $[G]$ matrices

$\{X\}$ = unknown displacements or tractions

$\{B\}$ = specified displacements or tractions

The unknown boundary displacements and tractions can now be determined. The BEM does provide techniques for directly calculating tractions and displacements at internal points. However, results at internal points are not needed for this particular problem.

The SSI problem which we are interested in solving can be modeled by using a finite element model for the structure and a boundary element model for the foundation. The following is a summary of Vallabhan's procedure for combining a linear boundary element with linear finite elements. For the FEM model of the structure:

$$[K]\begin{Bmatrix} u_s \\ u_i \end{Bmatrix} = \begin{Bmatrix} F_s \\ F_i \end{Bmatrix}$$

where

$u_s$ = displacements of the structure not in contact with the foundation

$u_i$ = displacements at interface of structure and foundation

$F_s$ = forces on structural nodes not in contact with the foundation

$F_i$ = forces on interface nodes

$[K]$ = stiffness matrix of structure

For the BEM model of the foundation:

$$[H]\begin{Bmatrix} u_i \\ u_F \end{Bmatrix} = [G]\begin{Bmatrix} T_i \\ T_F \end{Bmatrix}$$

where

$u_i$ = displacements at interface of structure and foundation

$u_F$ = displacements of the foundation not in contact with the structure

$T_i$ = interface tractions

$T_F$ = foundation tractions

Assuming that the interface tractions and displacements are compatible between the finite element and boundary element models, the BEM equation reduces to:

$$[K_F]\{u_F\} = -\{F_B\} - \{f_B\}$$

$[K_F]$ = stiffness matrix of foundation

$F_B$ = equivalent nodal forces from the known tractions

$f_B$ = equivalent nodal forces from the known displacements

Although this method is useful for homogeneous problems, a major limitation is that general purpose computer software is not readily available which can combine a boundary element foundation with a finite element structure.

## Elastic Half-Plane

Wilson and Turcotte (1986) present an exact solution of the equations of elasticity for an elastic half-plane subjected to an arbitrary set of surface loads. This solution leads to the calculation of flexibility and stiffness matrices which relate concentrated loads and the corresponding displacements. The elasticity problem was solved using a complex variable formulation to calculate stresses and displacements within a half-plane subjected to several concentrated loads. Once the half-plane stiffness matrix is formed, it can be combined with the beam stiffness matrix using a procedure similar to that used by the BEM. These equations can then be solved to calculate the displacements, which lead to shears and moments within the beam.

This procedure gives an exact solution if it can be assumed that the foundation actually behaves as an elastic half-plane. However, the same limitations apply as for the BEM: (a) there is no readily available computer software to attach an elastic half-plane model of the foundation to a finite element model of the structure; and (b) this model is only valid for a homogeneous foundation.

## Finite Element Method

In the FEM approach, both the foundation and the structure are modeled using finite elements. While these two stiffnesses can be combined using a procedure similar to the BEM, this combination is not necessary since the foundation can simply be modeled along with the structure. The finite element model can also be used for foundations with varying depths and with nonhomogeneous materials. The main limitation is that this study assumes the foundation to be linearly elastic; however, material models are available for nonlinear foundation models if desired.

## Conclusion

Of the currently available procedures, the FEM is the most practical means for modeling the foundation effects on a structure since existing computer software is readily available and the method allows for modeling of a variety of foundations with different sizes, shapes, and materials.

# 3 Extent of Foundation Necessary in Finite Element Analysis

## Background

The purpose of this study is to determine the extent of the foundation necessary to produce accurate results which must be included in the finite element models to accurately produce stresses within the foundation that match those obtained from theory of elasticity solutions. This size of the foundation which must be included in the analysis is relevant for any type of structure, (i.e., beam, mat, or dam) to be placed on an elastic media. However, the size of foundation determined in this study may be larger than that necessary to produce convergence of stresses within the structure itself.

This study addresses three loadings on an elastic half-plane for which closed form solutions are available. The first load case is a uniform normal pressure over a finite length of the foundation surface. The second load case is a uniform shear pressure over a finite length of the surface. The third load case is an antisymmetric uniform normal pressure load over a finite length of the foundation with one half of pressure acting in the negative direction, while the other half of the pressure acts in the positive direction.

The grids used for the uniform normal pressure loadings are shown in Figures 1-10. Table 1 gives the dimensions of the models in terms of the base width (BW) of the applied pressure loading. The BW of the applied pressure is equivalent to the BW of the structure sitting on the foundation. The grids used for the uniform shear loading and the antisymmetric normal pressure loading were generated by adding mirror images about the center line of each grid. This addition resulted in grids for these unsymmetric load cases which were twice the width of the grids shown in Figures 1-10.

All grids are restrained from displacing horizontally along all vertical boundaries. The bottom horizontal boundary is restrained from displacing vertically. The bottom corner nodes are therefore restrained from moving either horizontally or vertically. These boundary conditions allow for symmetrical behavior for the grids shown in Figures 1-10 and are also valid for the grids used for the unsymmetric load cases.

The finite element runs are all made using the general purpose finite element program, GTSTRUDL.[1] The element used is the "IPLQ" element which is a four-node isoparametric element that uses a linearly varying displacement function. The value of the modulus of elasticity for this problem is not important since the foundation is a homogeneous foundation and only stresses are being evaluated. A Poisson ratio of 0.499 was used for the finite element solution since the closed form solution assumed an incompressible media.

The nodes used for comparison lie on a diagonal line starting at the center of the load and running along an angle of 45 deg from the horizontal as shown in Figure 11. All grids have the same mesh density along this line used for comparison.

The equations and descriptions of angles used in the calculation of stresses by the closed form solution for the uniform load are shown in Figure 12. Figure 13 gives the equations and descriptions of angles used to calculate closed form stresses for the uniform shear loading. The antisymmetric normal pressure load case is calculated by applying a upward pressure on the left of the center line and a downward pressure on the right of the center line as shown in Figure 14. The closed form and finite element results are tabulated in Table 2 and plotted in Figures 15-17. The finite element results for horizontal stresses do not agree closely with the closed form values since the density of the mesh in the area of high stress gradients was not sufficient. The horizontal stresses tabulated on Table 2 and plotted in Figure 15 demonstrate these errors. However, the results for the shear and vertical stresses are predicted very accurately for the larger finite element grids. The finite element shear stresses at Point 11 for a uniform normal pressure are 26.9 percent in error for Model 3 and only 7.6 percent in error for Model 4. Similar magnitudes of error were obtained for the shear stresses from the other two load cases. The finite element vertical stresses at Point 11 are 4.5 percent in error for Model 3 and 1.4 percent in error for Model 4. The closed form and finite element results are tabulated in Table 3 and plotted in Figures 18-20 for the uniform shear load and in Table 4 and Figures 21-23 for the antisymmetric load case. Table 5 gives a list of the percentage of error for the vertical

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[1] GTSTRUDL is a general-purpose finite element program owned and maintained by the GTICES Systems Laboratory, School of Civil Engineering, Georgia Institute of Technology. Program runs used in this report were made on the Control Data Corporation, Cybernet Computer System.

stresses for all load cases for Models 3 and 4. In these analyses positive stresses are compressive, and negative stresses are tensile.

## Conclusions

This study shows that a finite element grid must include a foundation depth of at least three times the BW of the structure in order to obtain foundations with vertical stresses with less than 10 percent difference from the theory of elasticity solution. This study has not addressed the problem of convergence of stresses within the structure.

# 4 Effect of Foundation Size on Stresses Within the Structure

## Background

The results of Chapter 3 indicated that a foundation model of depth equal to at least three times the BW of the dam was necessary to achieve convergence of the vertical stresses in the foundation to within 10 percent of the stresses from the closed form solution. This study also indicated that a more shallow foundation depth may be sufficient to achieve convergence of stresses within the dam. Based upon this information, the maximum foundation depth studied herein is three times the BW of the dam.

The foundation-structure interaction is observed by varying the size of the foundation model while maintaining a constant gravity dam model. An examination of the stresses within the dam was then made to determine what conclusions could be drawn concerning stress convergence.

## Dam Model

The general configuration of a typical dam (Figure 24) was used as the gravity dam in this study. The finite element mesh used to model the dam in the foundation size study that utilized 6 elements along the dam-foundation interface has a total of 102 elements and 365 nodes as shown in Figure 25.

## Foundation Models

Three foundation models were considered in the analysis. The sizes of each foundation model presented in Table 6 are all a function of the BW of the gravity dam and have six elements along the base of the dam model, as shown in Figure 25. The FEM meshes, node, and element numbering are shown in Figures 26, 27, and 28.

## Material Properties

A Poisson's ratio of 0.2 for both the rock and concrete, a concrete modulus of elasticity (Ec) of $4.0 \times 10^6$ pounds per square inch (psi) and a foundation deformation modulus of elasticity (Er) of $4.0 \times 10^6$ psi were used in these analyses.

## Boundary Conditions

The boundary nodes for all foundation models were input as rollers with the exception of the lower right and left corners, which were fixed.

## Loads

Hydrostatic loading from the reservoir was applied to the foundation elements upstream of the dam and to the upstream face of the dam. These loads were input as uniform edge loads on the upstream foundation elements and as uniformly varying edge loads on the upstream face elements of the dam. The weight of the concrete dam was input as body forces for the elements within the dam equal to 150 pounds per cubic foot (pcf). The weight of the rock foundation was ignored in the analyses. Uplift on the base of the dam and pore pressure in the foundation was not considered in the analyses.

## Analysis Procedure

All computer runs were made using the program GTSTRUDL. One run was made for each of the foundation models. The results of these analyses were examined for the effects of the foundation size on stresses within the dam.

## Results of Model Size Study

The impact of varying the size of the foundation model upon stresses in the dam is illustrated in Tables 7, 8, and 9. These tables show the vertical, horizontal and shear stresses (Syy, Sxx and Sxy), respectively, for the lower two rows of nodes in the gravity dam. Examination of these tables indicates that there is not a significant change in the stresses in the lower portion of the dam, even when the foundation model size is changed by a factor of more than three.

In general, as foundation model size increases, vertical stresses in the heel and toe region become more compressive and are reduced in the center portion of the base. Shear and horizontal stresses were distributed more towards the toe as model size was increased. Stresses at the extreme heel of the dam-foundation interface changed more dramatically than in the interior. This change became less dramatic above the dam-foundation interface.

Vertical displacements were greatly effected by changes in model size, increasing by more than 20 percent between Models 1 and 2 and by more than 50 percent between Models 1 and 3. However, this variation of vertical displacement with foundation depth is as expected for a linear elastic foundation with a constant loading. Horizontal displacements decreased as model size increased. Table 10 shows the effects of model size on the horizontal and vertical displacements.

Stress contour plots of vertical, horizontal and shear stresses for foundation Model 1 ($3 \times 5$ BW) are shown in Figures 29, 30, and 31, respectively.

## Conclusions

A foundation model of depth and width equal to 1.5 and 3.0 times the BW of the dam, respectively, is sufficient to achieve accurate stress results within the dam.

# 5 Effect of Foundation Stiffness on Stresses Within a Gravity Dam

## Scope

This section examines the impact upon dam stresses of varying the ratio of rock deformation modulus to concrete elastic modulus. The foundation-structure interaction was tested in Chapter 4 by varying the size of the foundation model while maintaining a constant gravity dam section as shown in Figure 24. An examination of the stresses within the dam was made to determine what conclusions can be drawn concerning stress convergence. The results of Chapter 3 indicated that a foundation model of depth equal to at least three times the BW of the dam was necessary to achieve convergence of foundation stresses to within 10 percent of a closed form solution. The results of Chapter 4 indicated that a more shallow depth may be sufficient to achieve convergence of stresses within the dam. Based upon these works, the maximum depth studied herein is three times the BW of the dam (Model 3).

The gravity dam mesh that was used in this study is finer than the mesh used in the size studies in Chapter 4 in order to determine the effect of mesh density upon stresses at the heel and toe of the dam. This finer mesh shown in Figure 32 has 10 elements along the dam-foundation interface.

## Material Properties

A Poisson's ratio of 0.2 for both rock and concrete and a concrete modulus of elasticity of $4.0 \times 10^6$ psi were used throughout the analyses. The foundation deformation modulus of elasticity was varied from $0.2 \times 10^5$ to $12 \times 10^6$ psi as shown in Table 11, with an additional run with the base of the dam fixed to simulate an infinitely rigid foundation. These runs utilized the 10 base-element gravity dam and foundation model as shown in Figure 32.

## Boundary Conditions

The boundary nodes for all foundation models were input as rollers with the exception of the lower right and left corners, which were fixed.

## Loads

Hydrostatic loading from the reservoir was applied to the foundation elements upstream of the dam and to the upstream face of the dam. These loads were input as uniform edge loads on the upstream foundation elements and as uniformly varying edge loads on the upstream face elements of the dam. The weight of the concrete dam was input as body forces on the elements within the dam equal to 150 pcf. The weight of the rock foundation was ignored in the analysis. Uplift on the base of the dam and pore pressure in the foundation was not considered in these analyses.

## Analysis Procedure

All computer runs were made using the program GTSTRUDL. The analysis results from Model 3 (material property condition C from Table 11) of the Chapter 4 study were used in this study also. Four additional runs using Model 3 and material property conditions A, B, D, and E and one run with the fixed base model (F) were made for this part of the study. Table 12 summarizes the additional GTSTRUDL runs analyzed.

## Results of Foundation Stiffness Study

The effect of foundation stiffness on dam stresses was studied by varying the modulus of elasticity of the foundation elements in Model 3. The results summarized in Tables 13, 14, and 15 indicate that foundation stiffness has a significant impact upon stresses in the dam. It should be noted that the Model 3 used for this study differs from the same size foundation model used in the Chapter 4 study. The Chapter 4 model used 6 elements at the dam-foundation interface. In this study, the dam-foundation model used 10 elements above the base, as shown in Figure 33. This refinement was made in order to gain a better understanding of the stresses which occur at reentrant corners in FEM analyses.

Figure 34 shows the effect on the vertical stress distribution of using the finer heel and toe mesh. This figure shows that as the mesh was refined, the magnitude of the extreme heel and toe stress was increased, but the length of base over which the high stresses occurred was decreased. The use of an even finer mesh would probably show that the zone of high stress concentration can be reduced significantly.

Table 13 shows the vertical stresses for the various Er/Ec ratios studied. The distribution of vertical (Syy) stresses at the interface between the dam and the foundation shifted from the extreme nodes towards the center nodes as the foundation stiffness increased. Figure 35 shows this stress shift for selected nodes and also indicates that the stresses are approaching an asymptotic value as the Er/Ec ratio approaches 3.0. Figure 36 shows that the stresses become more compressive at the interior nodes and become less compressive at the end nodes as the foundation stiffness increased. Horizontal stresses shown in Table 14 were distributed more evenly across the plane of the nodes, and more of the horizontal load was resisted by the interface nodes as foundation stiffness increased. Accordingly, shear stresses also increased with increasing foundation stiffness.

Both horizontal and vertical displacements at the interface were reduced rapidly as foundation stiffness increased. Tables 16 and 17 show the effect of foundation stiffness on displacements. Figure 37 demonstrates graphically that, as expected, displacements follow the same patterns as stresses, i.e., they converge as the Er/Ec ratio approaches 3.0.

Relative displacements are shown in Tables 18 and 19. Table 19 shows that the relative vertical displacements above the interface do not change appreciably for Er/Ec ratios greater than 1.0. At Er/Ec=1.0, the displacements are within 57 percent of those for Er/Ec equal to infinity. Relative horizontal movements near the interface followed a similar pattern and are within 10 percent of the Er/Ec ratio of 1.0. In the upper portions of the dam, relative movements reduced as foundation stiffness increased.

Stresses at the plane approximately two thirds of the height of the dam above the interface were not significantly affected by changes in the foundation stiffness.

## Plots of Results

Vertical, horizontal, and shear stresses for modulus ratios of 0.05, 0.25, 1.0, 1.75, and 3.00 are given in Figures 38-52, respectively. The CASE program for plotting of shears, moments, and thrust (CSMT) was used to plot the results of the stiffness study along a plane through the foundation structure interface. These plots are shown in Figures 53-57 for modulus ratios of 0.05, 0.25, 1.0, 1.75, and 3.0, respectively.

Relative vertical displacements, although small in magnitude, more than doubled when the foundation size ratio increased from 1.78 to 3.33. Relative horizontal displacements decreased when the model size ratio increased to 1.78; however, they decreased when the size ratio increased to 3.33.

## Conclusions

Foundation stiffness has a significant effect upon the distribution of stresses in the dam, especially with Er/Ec ratios approaching 1.00, and therefore should be selected carefully.

As foundation stiffness increases, the effect of foundation stresses upon stresses within the dam is decreased. Dam stresses for Er/Ec ratios of greater than 3.0 did not yield significantly different results than for Er/Ec = 3.0 and were not much greater than the results for Er/Ec = 1.0.

As the Er/Ec ratio increases, vertical stresses near the rock-concrete interface become more compressive near the center line of the base and less compressive at the heel and toe of the structure.

The dam-foundation interface resists more of the driving forces on the dam as the foundation stiffness increases; i.e., shear and horizontal stresses at the interface increased with increased foundation stiffness.

A fine mesh should be used to model the structure foundation interface, especially, at reentrant corners such as the heel and toe of the dam.

# References


Winkler, E. (1867). "On elasticity and strength," H. Dominicus, Prague, Czechoslovakia.

Haliburton, T. A. (1971). "Soil structure interaction," Technical Publication No. 14, School of Civil Engineering, Oklahoma State University, Stillwater, OK.

Dawkins, W. P. (1982). "User's guide: computer program for analysis of beam-column structures with nonlinear supports (CBEAMC)," Instruction Report K-82-6, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Reese, L. C., and Matlock, H. (1956). "Non-dimensional solutions for laterally loaded piles with soil modulus assumed proportional to depth," *Proceedings, Eighth Texas Conference on Soil Mechanics and Foundation Engineering.*

Nogami, T., and Lam, L. C. (1986). "Soil-beam interaction analysis with a two-parameter layer soil model: homogeneous medium," Technical Report ATC-86-3, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Vallabhan, C. V. G., and Sivakumar, J. (1986). "The application of boundary-element techniques for some soil-structure interaction problems," Technical Report ATC-86-2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Wilson, H. B., and Turcotte, L. H. (1986). "Foundation interaction problems involving an elastic half-plane," Technical Report ATC-86-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

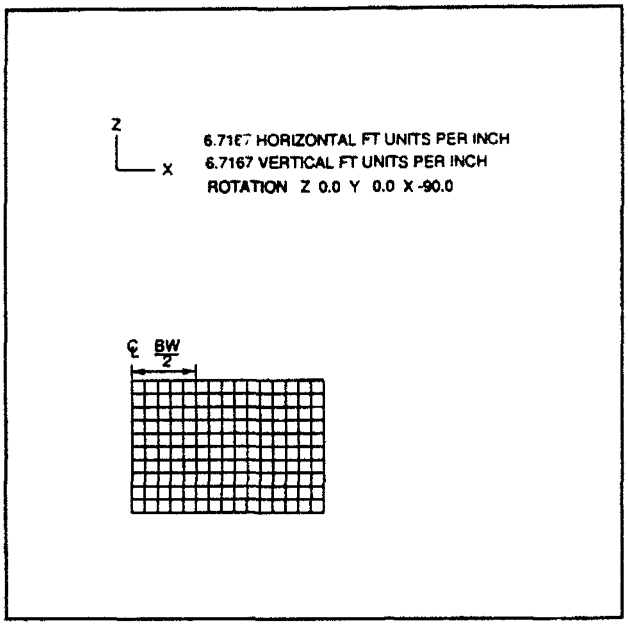



Figure 1. Model 1 (3 BW x 1 BW)

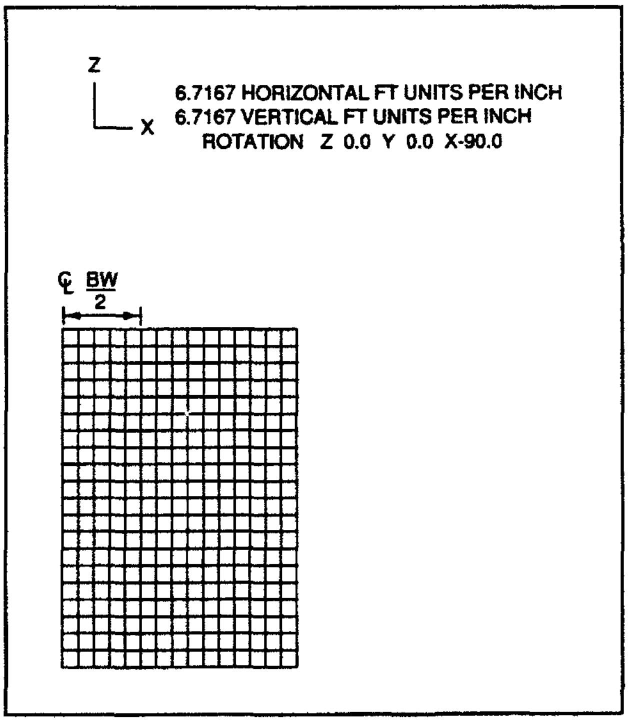



Figure 2. Model 2 (3 BW x 2 BW)

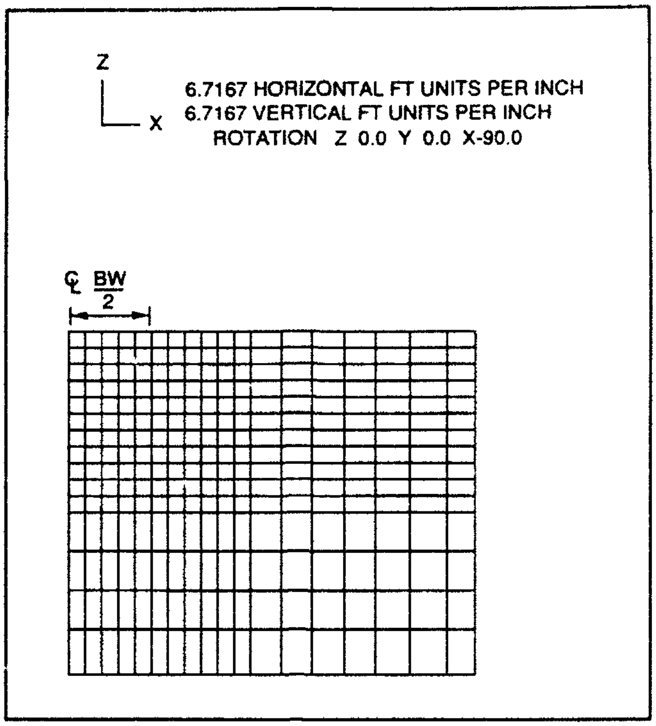



Figure 3. Model 3 (5 BW x 2 BW)

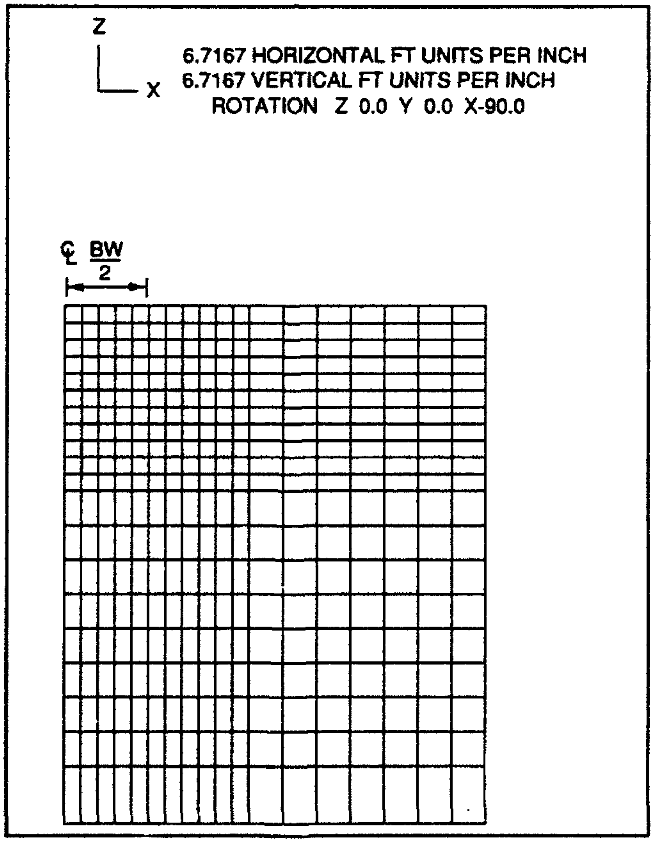



Figure 4. Model 4 (5 BW x 3 BW)

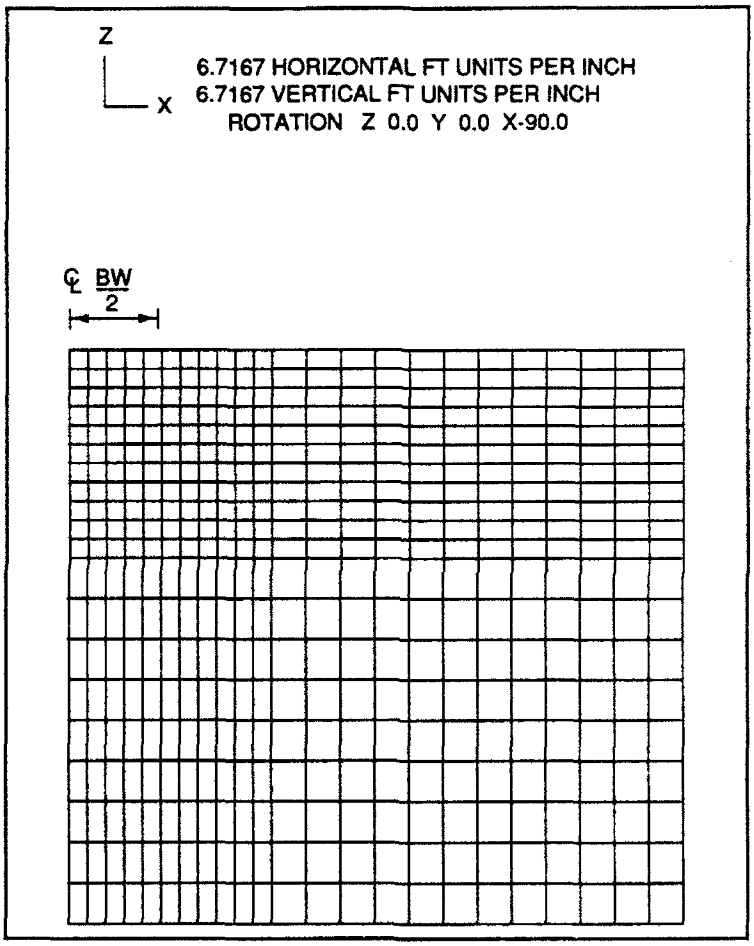



Figure 5. Model 5 (7 BW x 3 BW)

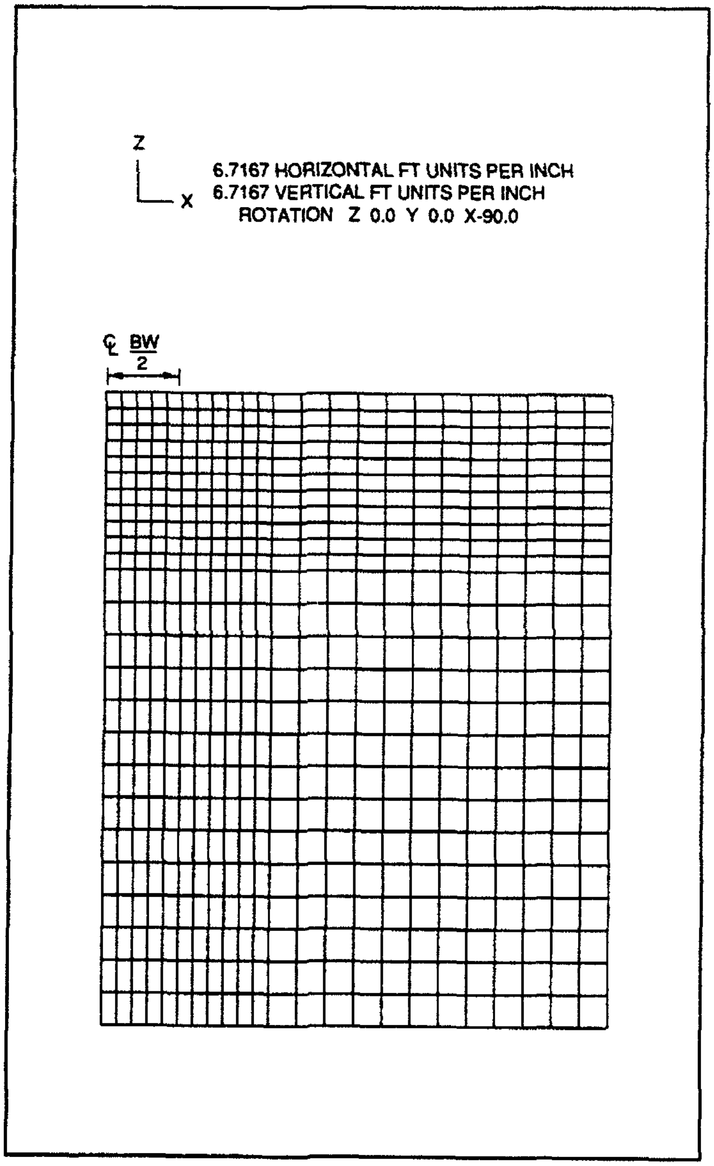



Figure 6. Model 6 (7 BW x 4 BW)

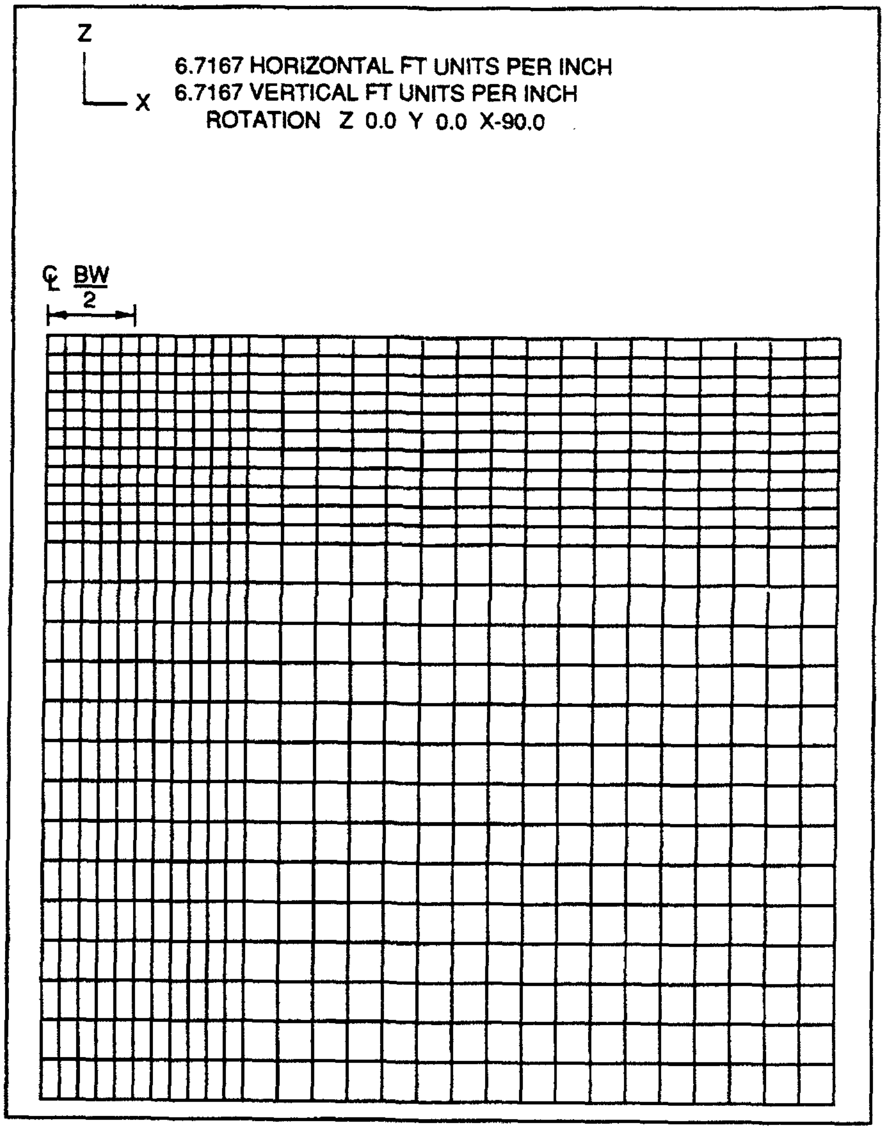



Figure 7. Model 7 (9 BW x 4 BW)

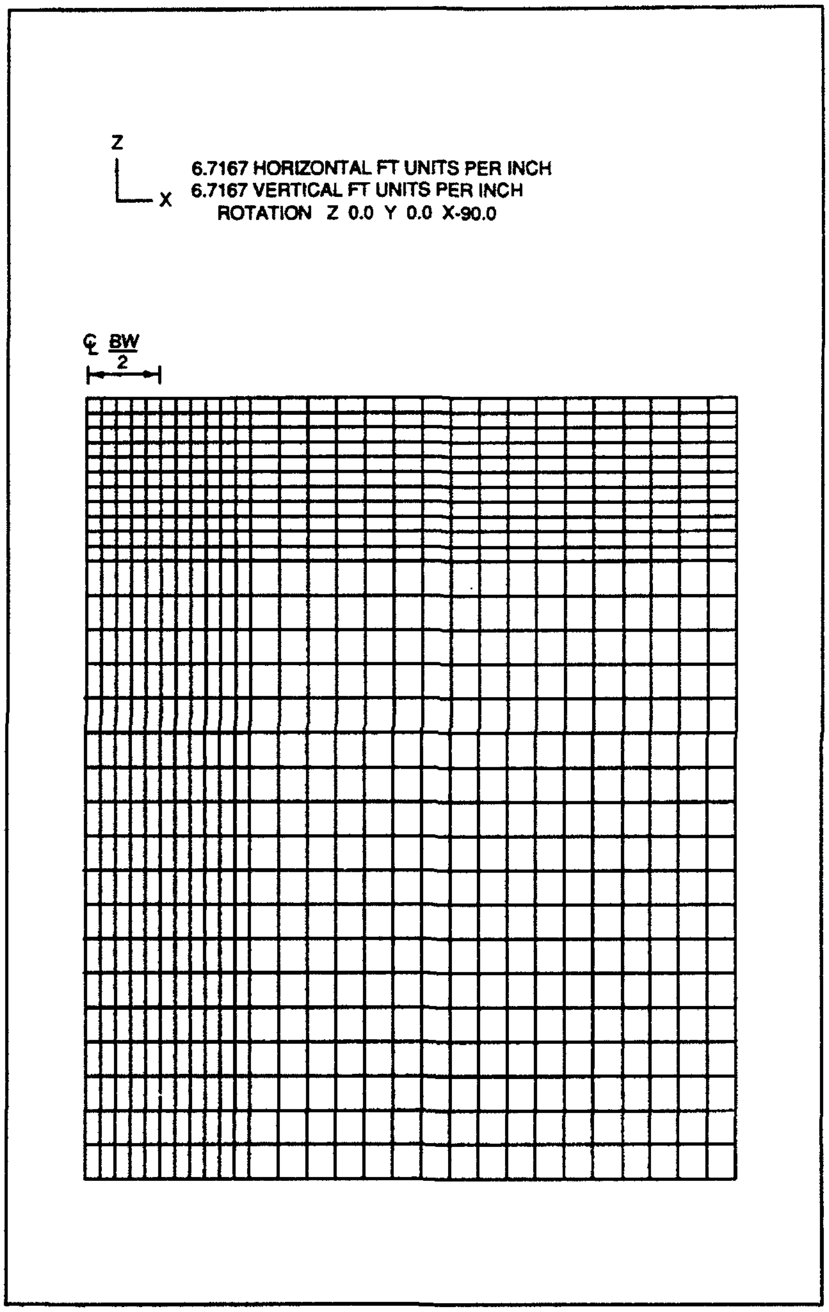



Figure 8. Model 8 (9 BW x 5 BW)

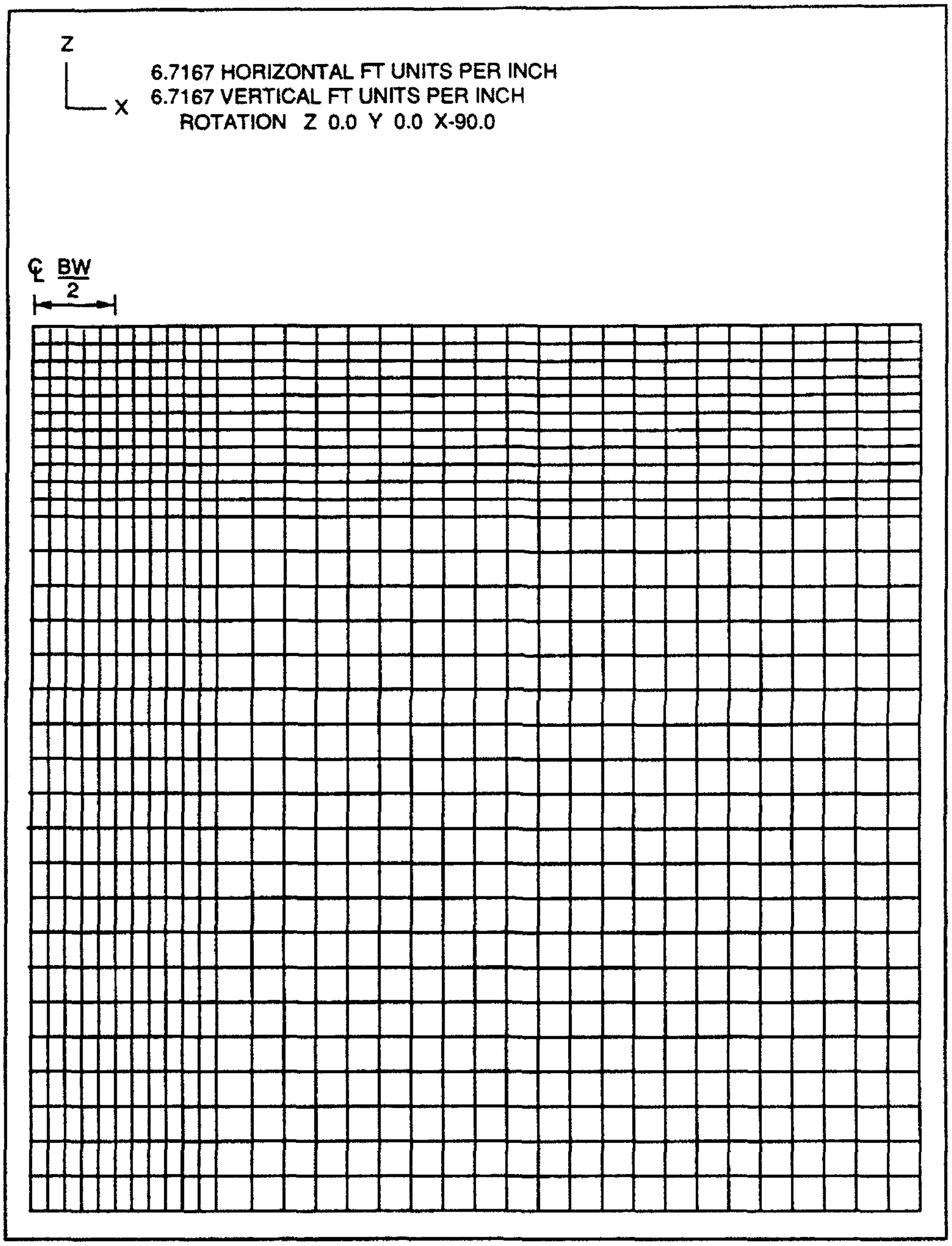



Figure 9. Model 9 (11 BW x 5 BW)

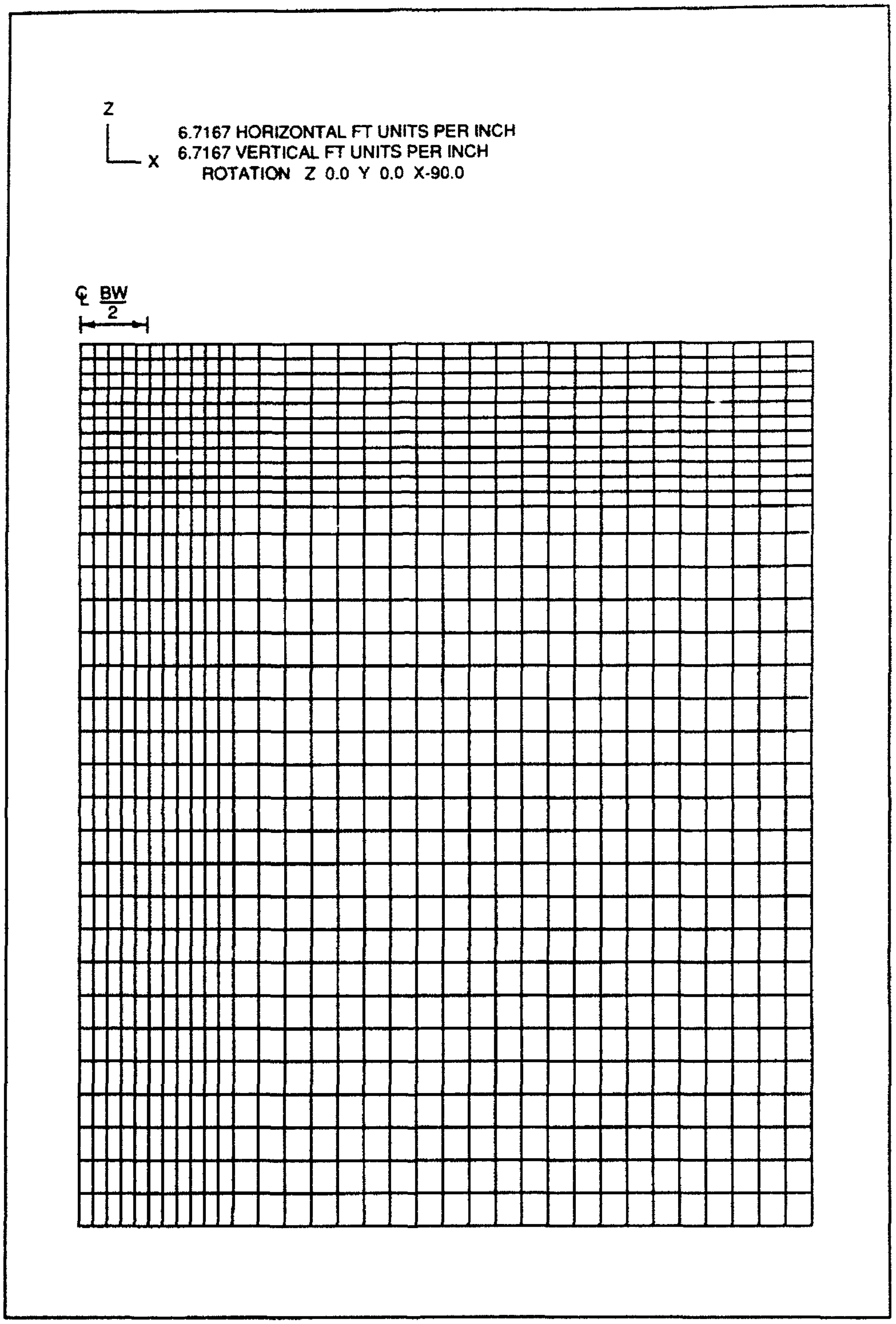



Figure 10. Model 10 (11 BW x 6 BW)

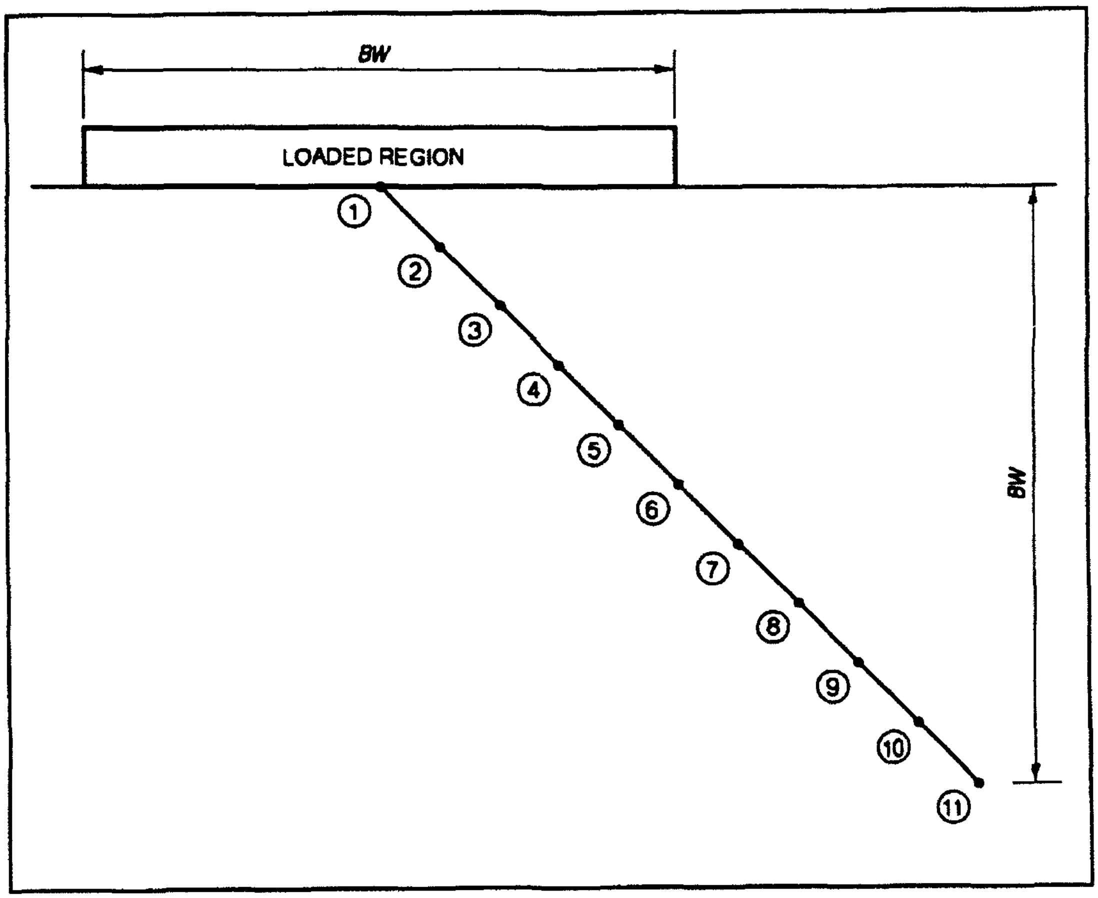
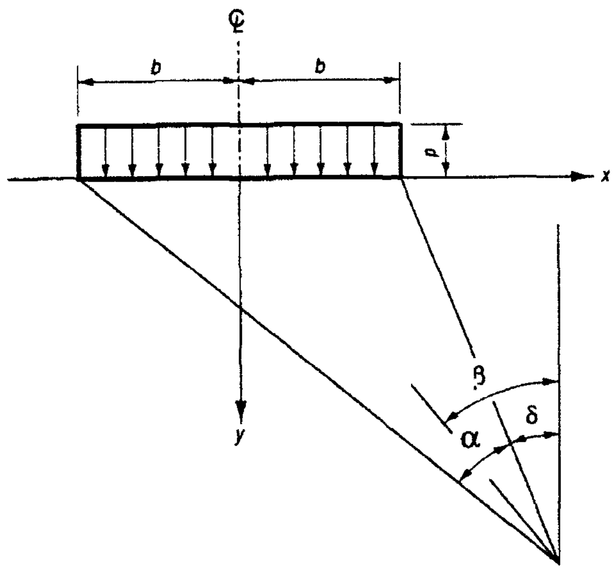



Figure 11. Nodes used for comparison




$$\beta = \delta + \frac{1}{2}\alpha$$

$$\sigma_{xx} = \frac{P}{\pi}\left(\alpha - \mathrm{SIN}\,\alpha \;\; \mathrm{COS}\,2\,\beta\right)$$

$$\sigma_{yy} = \frac{P}{\pi}\left(\alpha + \mathrm{SIN}\,\alpha \;\; \mathrm{COS}\,2\,\beta\right)$$

$$\tau_{xy} = \frac{P}{\pi}\,\mathrm{SIN}\,\alpha \;\; \mathrm{SIN}\,2\,\beta$$

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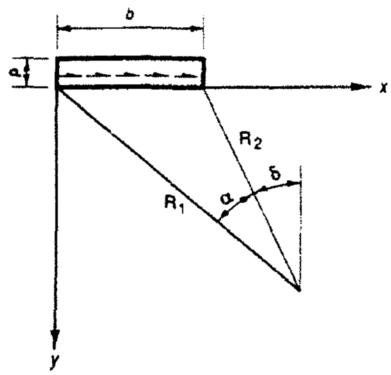
Figure 12. Closed form stresses for normal pressure loading (load case 1)




$$\sigma_{xx} = \frac{P}{\pi}\left[\mathrm{LOGE}\,\frac{R_1^2}{R_2^2} - \mathrm{SIN}\,\alpha\ \mathrm{SIN}(\alpha + 2\delta)\right]$$

$$\sigma_{yy} = \frac{P}{\pi}\left[\mathrm{SIN}\,\alpha\ \mathrm{SIN}(\alpha + 2\delta)\right]$$

$$\tau_{xy} = \frac{P}{\pi}\left[\alpha - \mathrm{SIN}\,\alpha\ \mathrm{COS}(\alpha + 2\delta)\right]$$

Figure 13. Closed form stresses for shear pressure loading (load case 2)

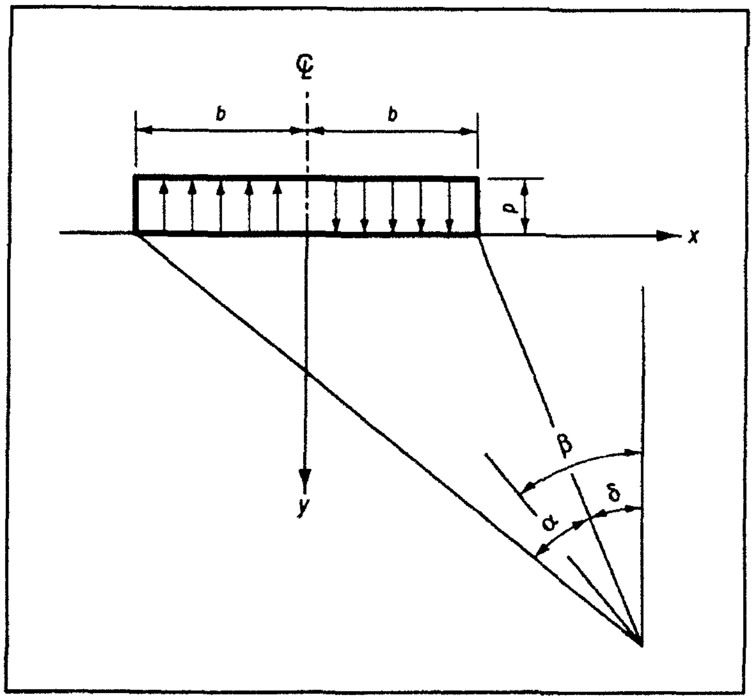



Figure 14. Closed form stresses for antisymmetric normal pressure loading (load case 3)

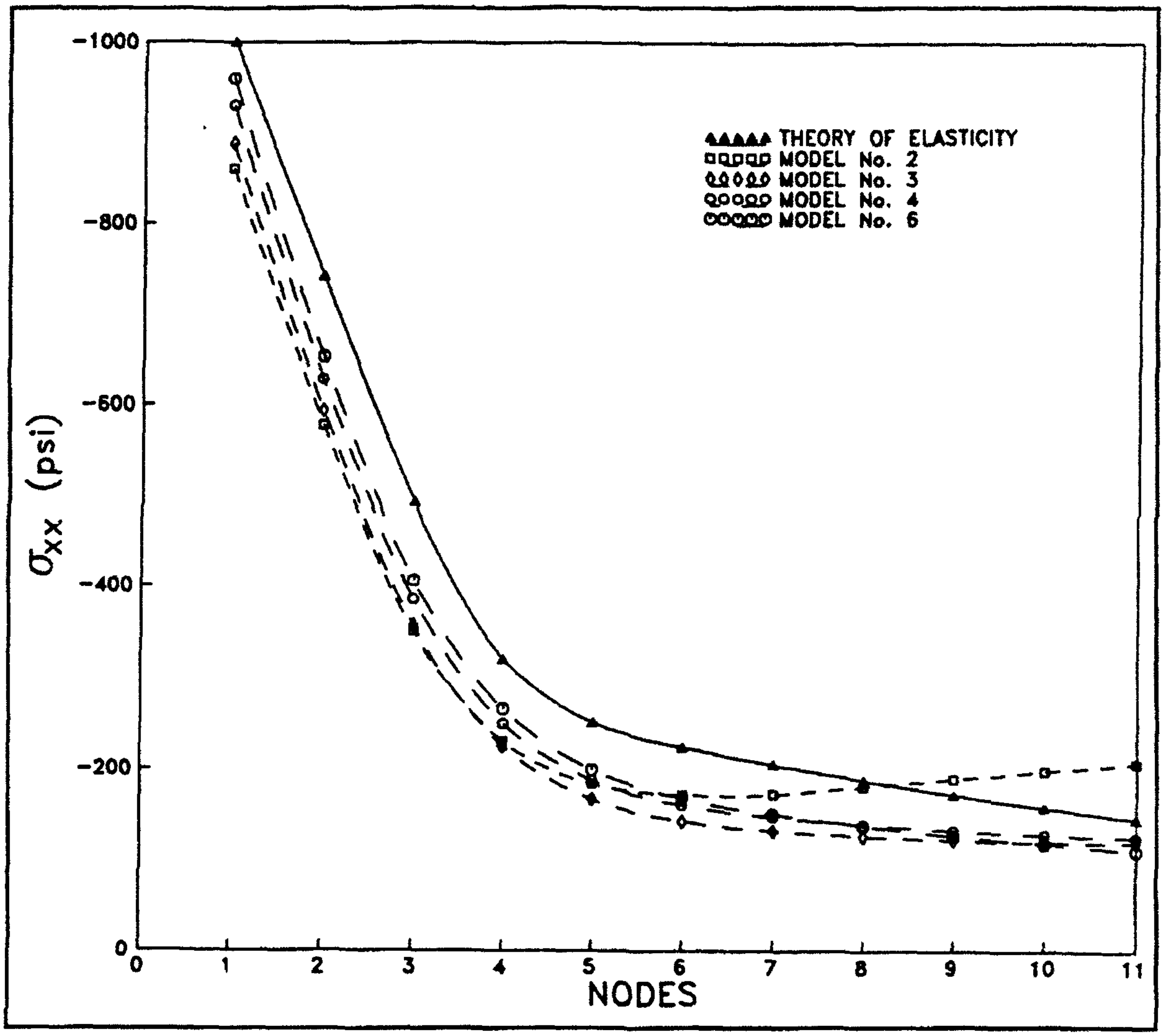



Figure 15. Plot of $\sigma_{xx}$ stress from finite element and closed form results for uniform normal pressure load

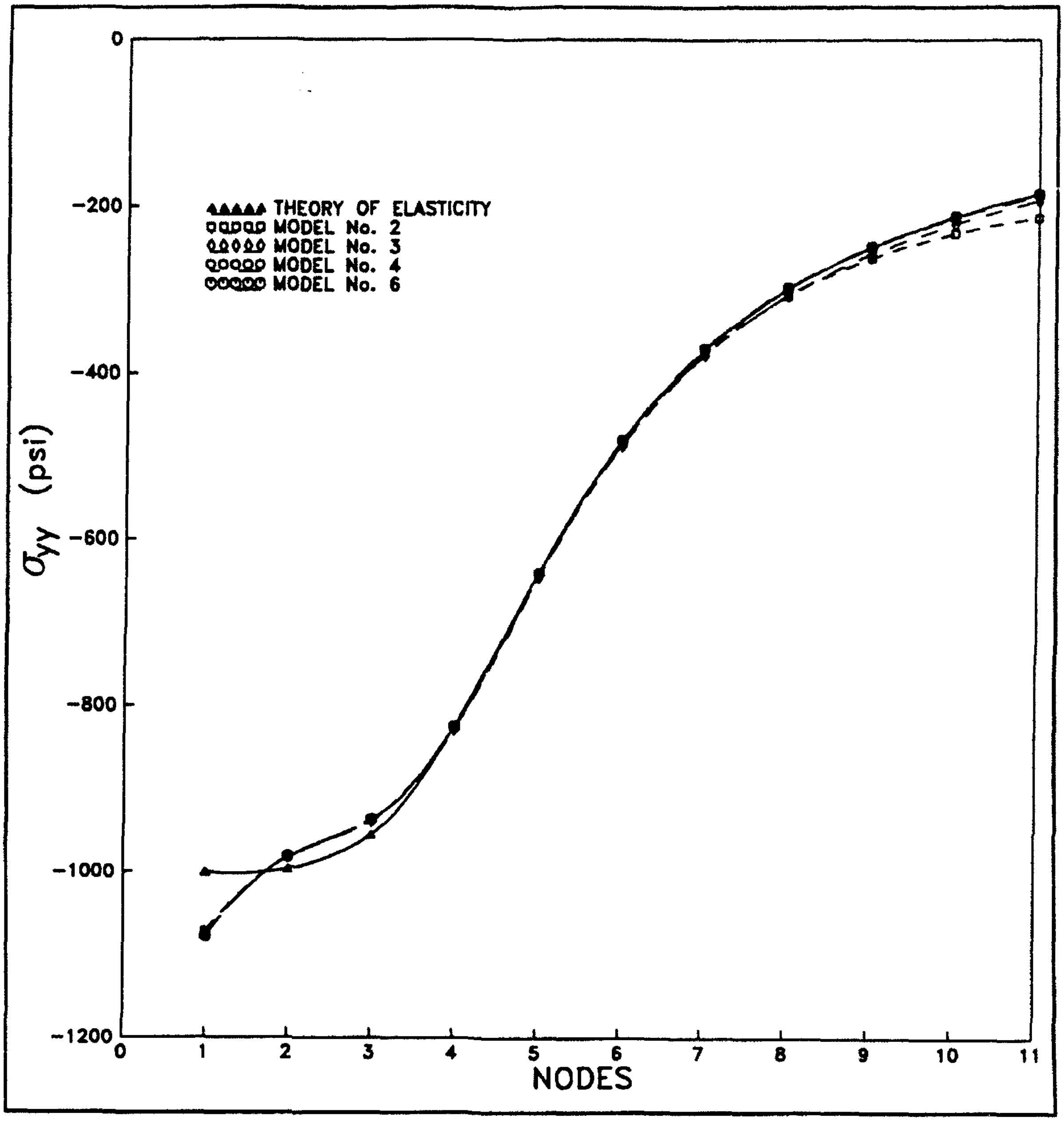



Figure 16. Plot of $\sigma_{yy}$ stress from finite element and closed form results for uniform normal pressure load

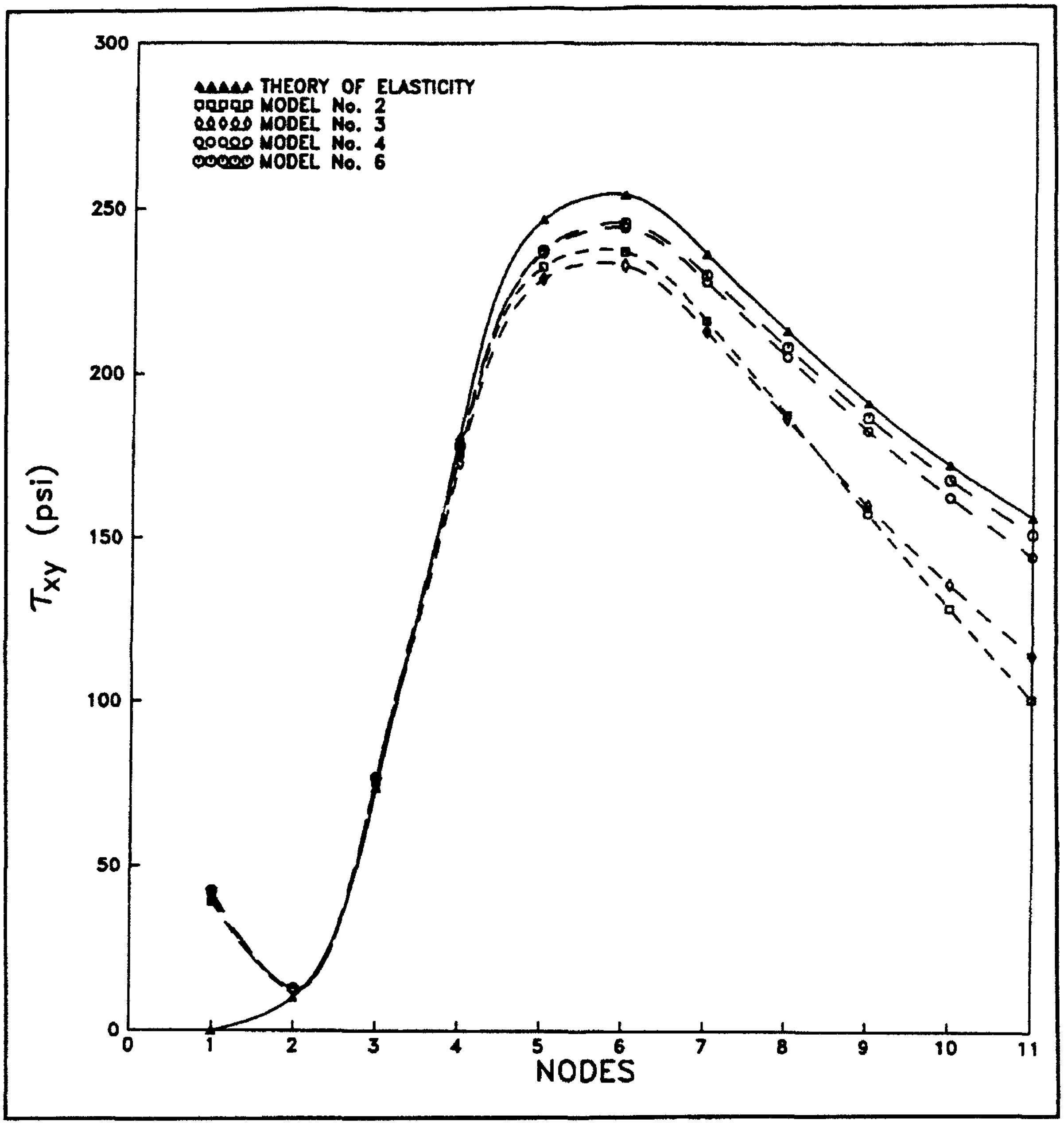



Figure 17. Plot of $\tau_{xy}$ stress from finite element and closed form results for uniform normal pressure load

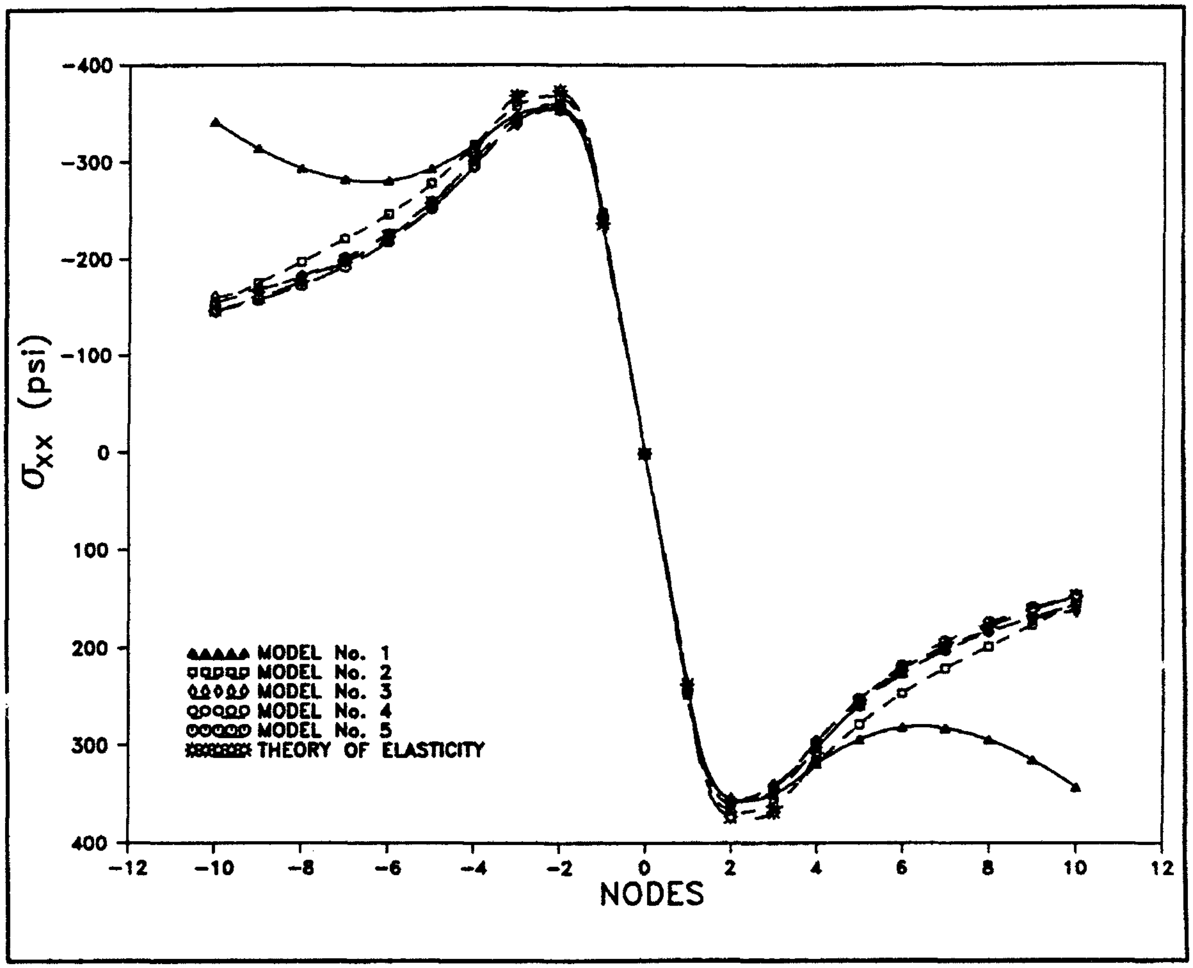



Figure 18. Plot of $\sigma_{xx}$ stress from finite element and closed form results for uniform shear load

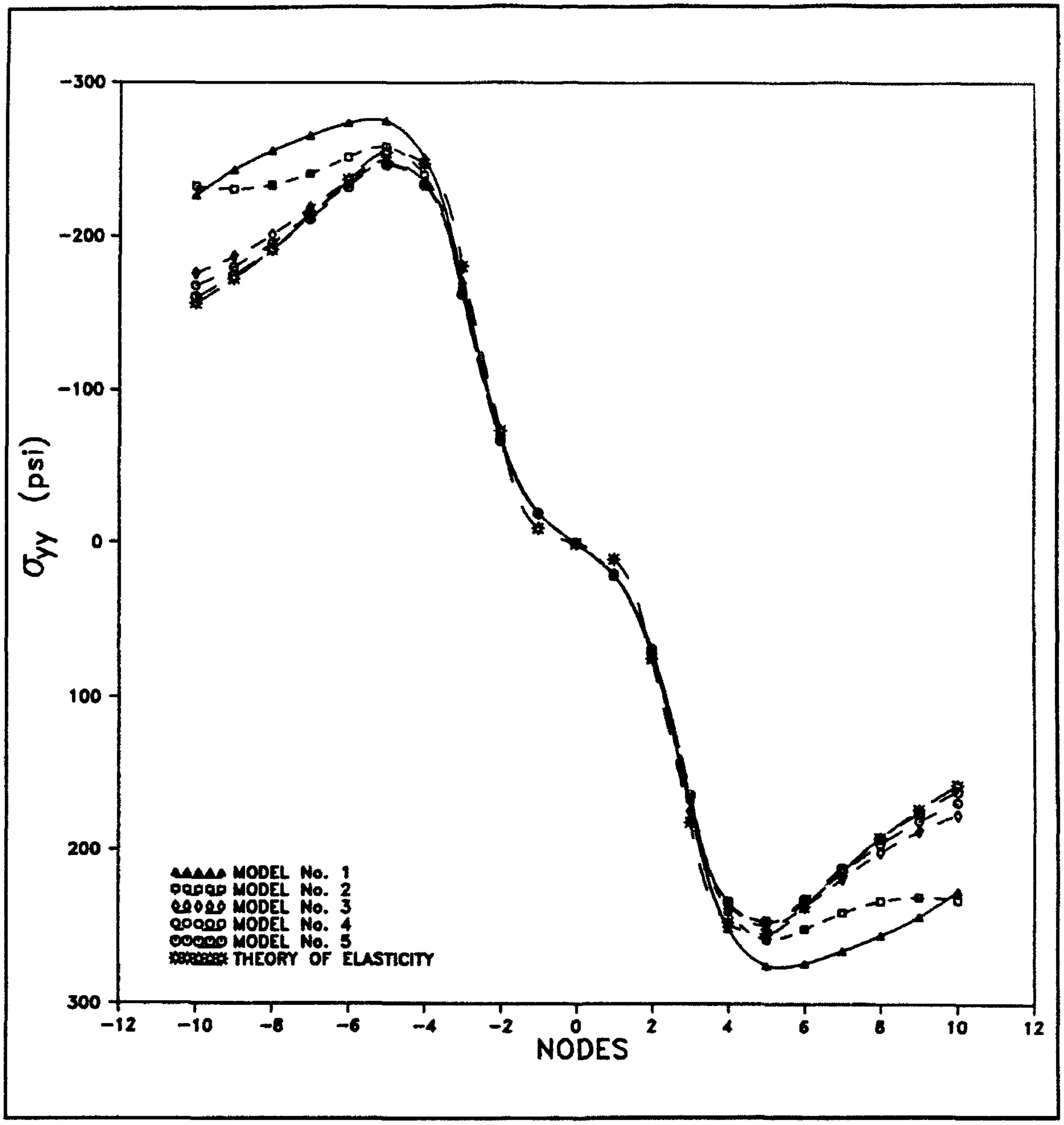



Figure 19. Plot of $\sigma_{yy}$ stress from finite element and closed form results for uniform shear load

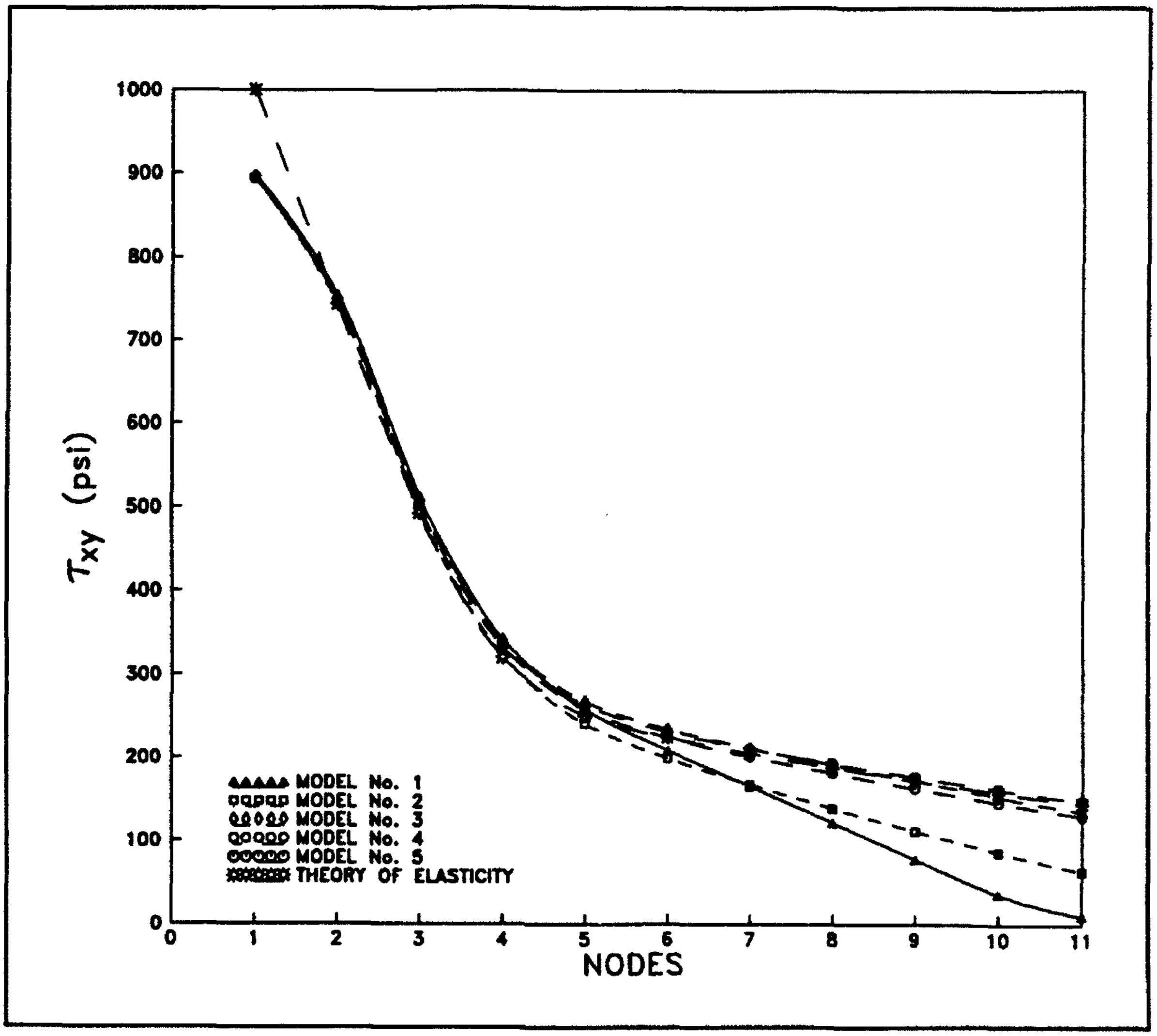



Figure 20. Plot of $\tau_{xy}$ stress from finite element and closed form results for uniform shear load

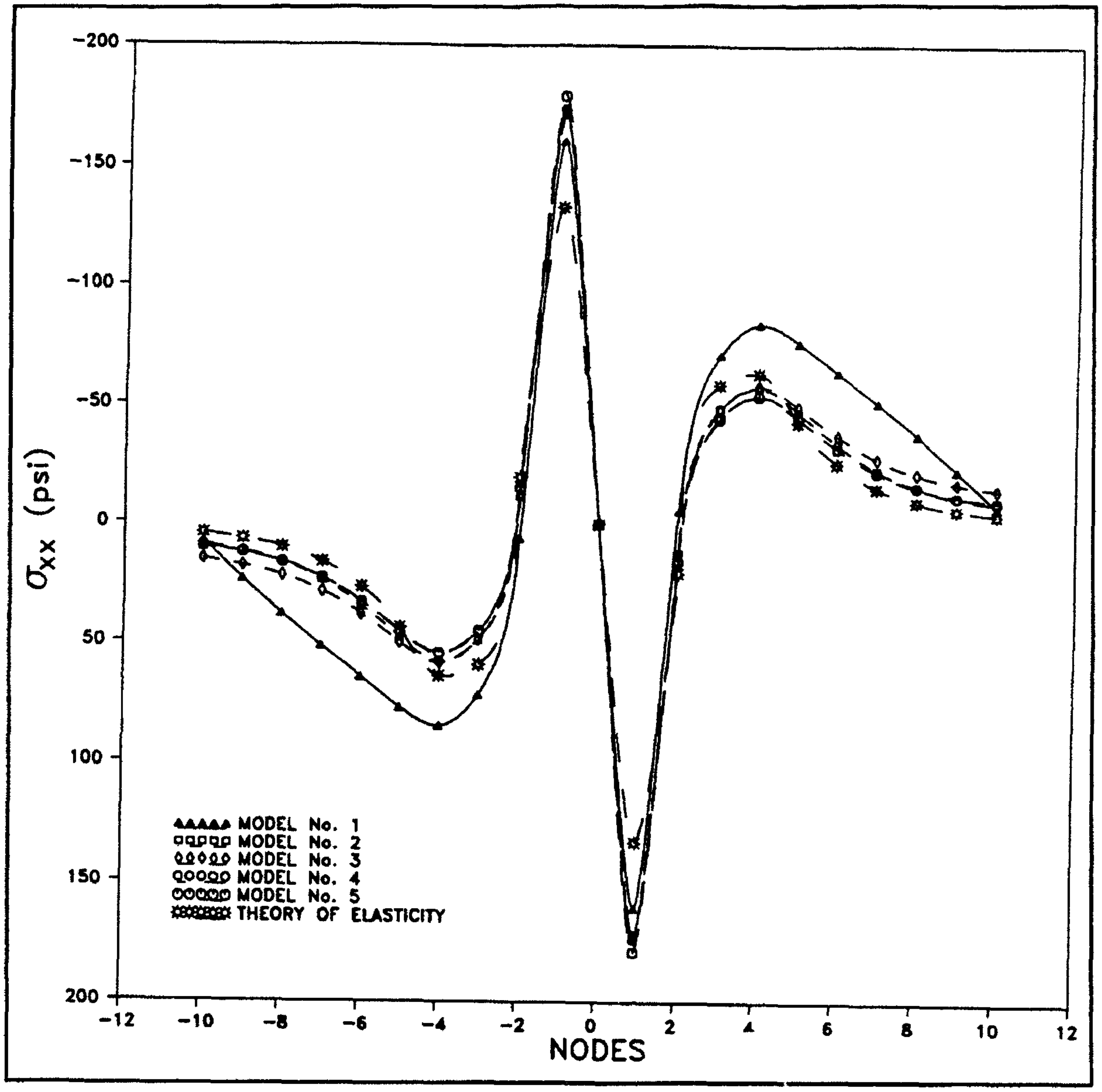



Figure 21. Plot of $\sigma_{xx}$ stress from finite element and closed form results for antisymmetric normal pressure

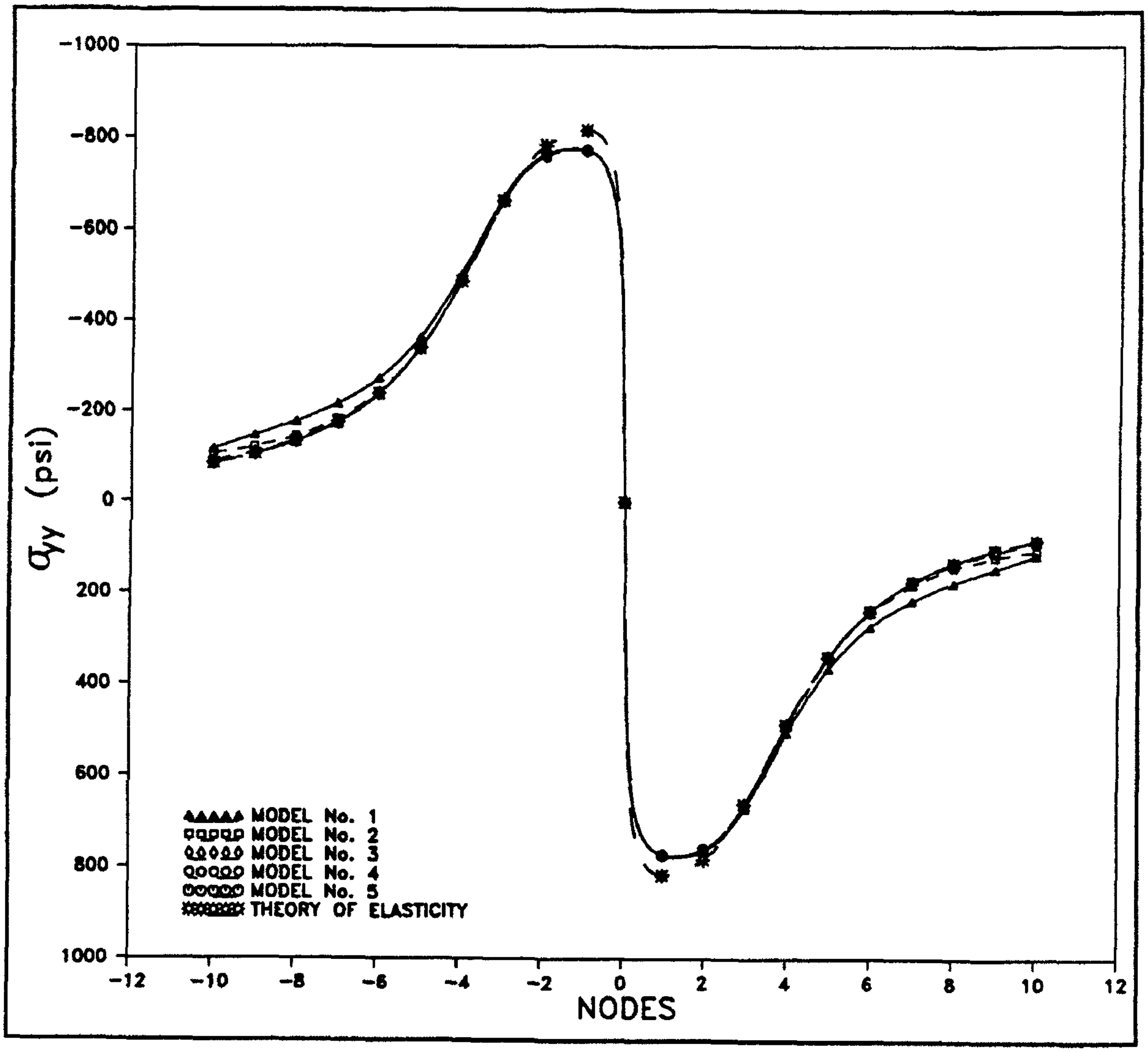



Figure 22. Plot of $\sigma_{yy}$ stress from finite element and closed form results for antisymmetric normal pressure

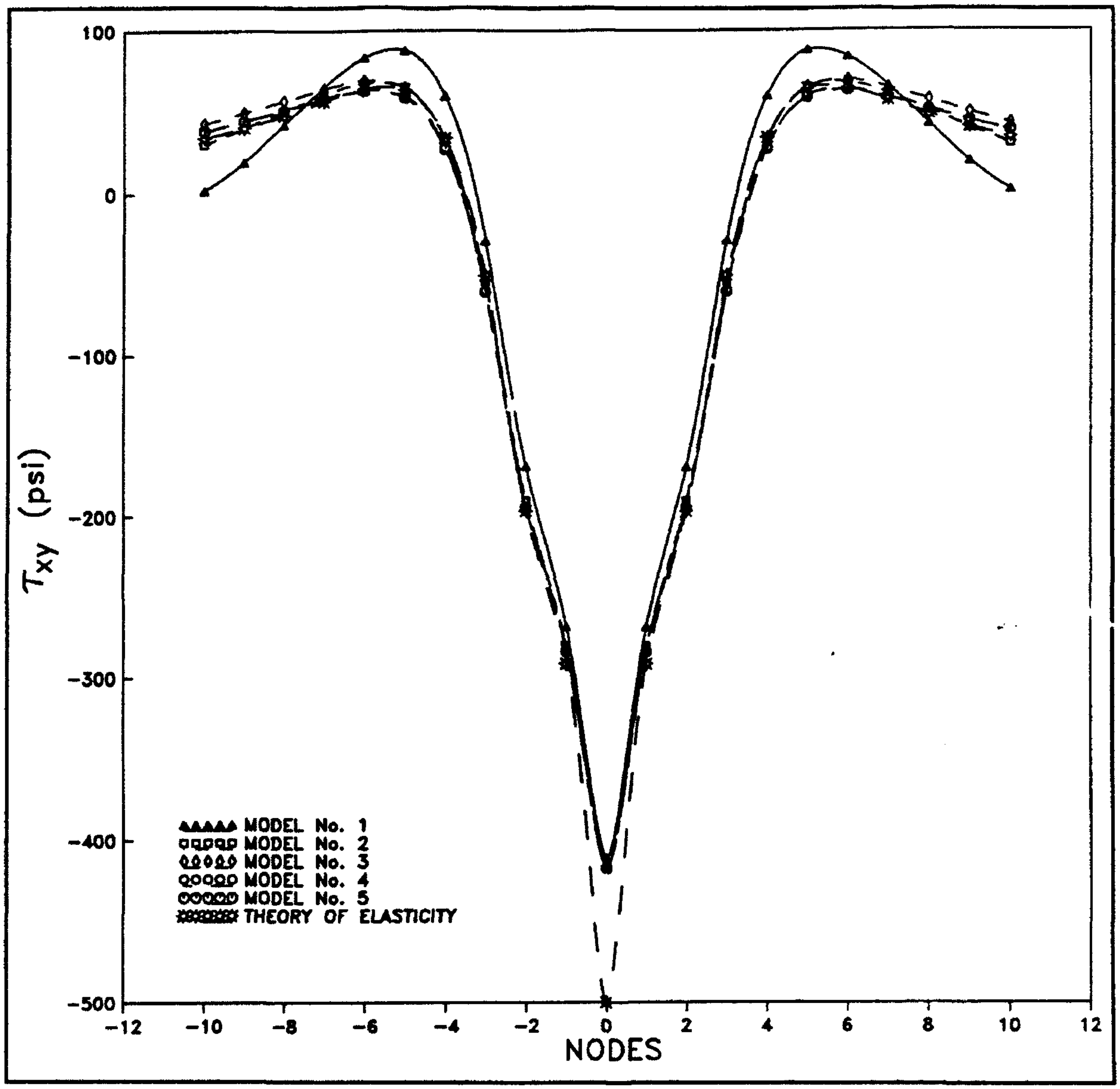



Figure 23. Plot of $\tau_{xy}$ stress from finite element and closed form results for antisymmetric normal pressure

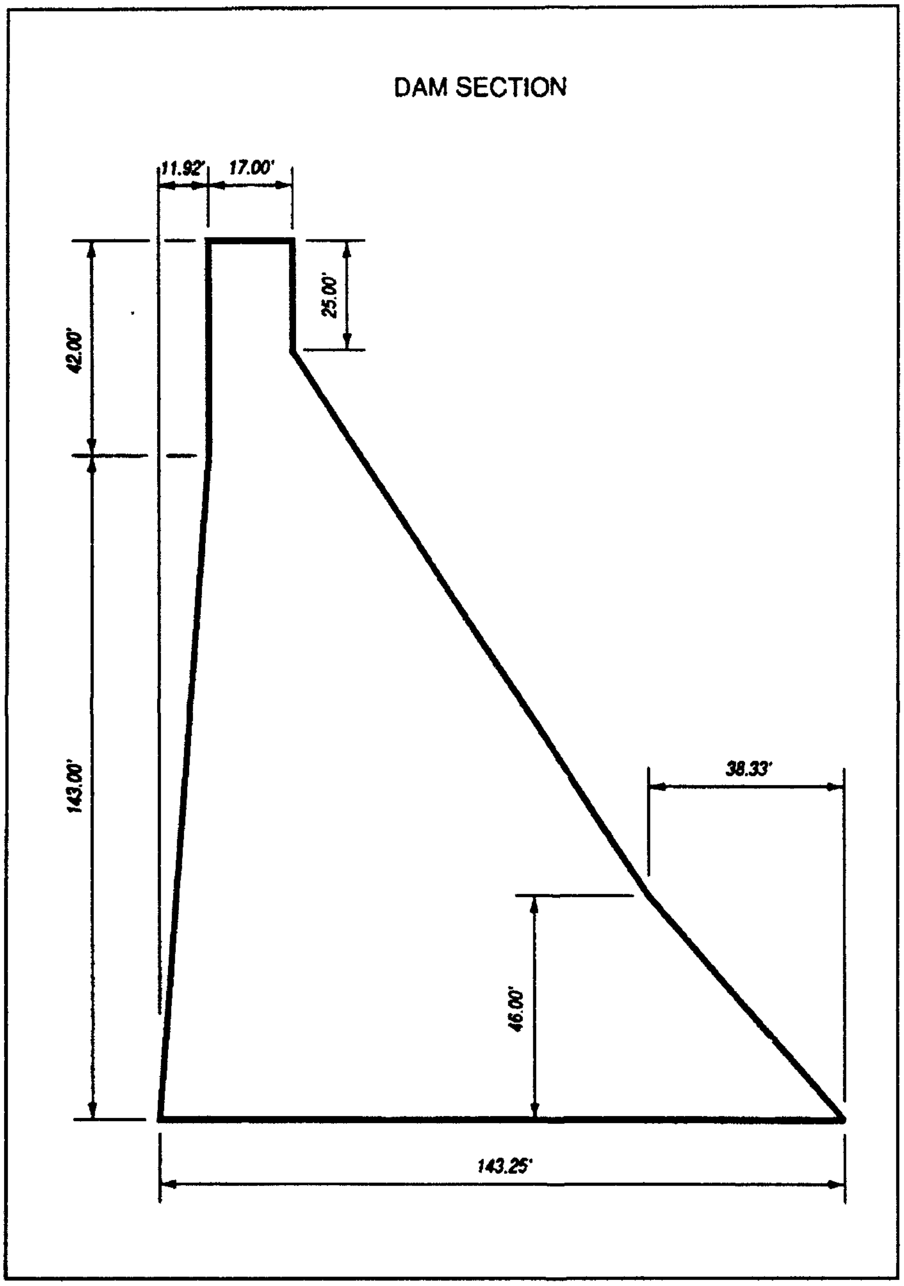



Figure 24. Gravity dam section

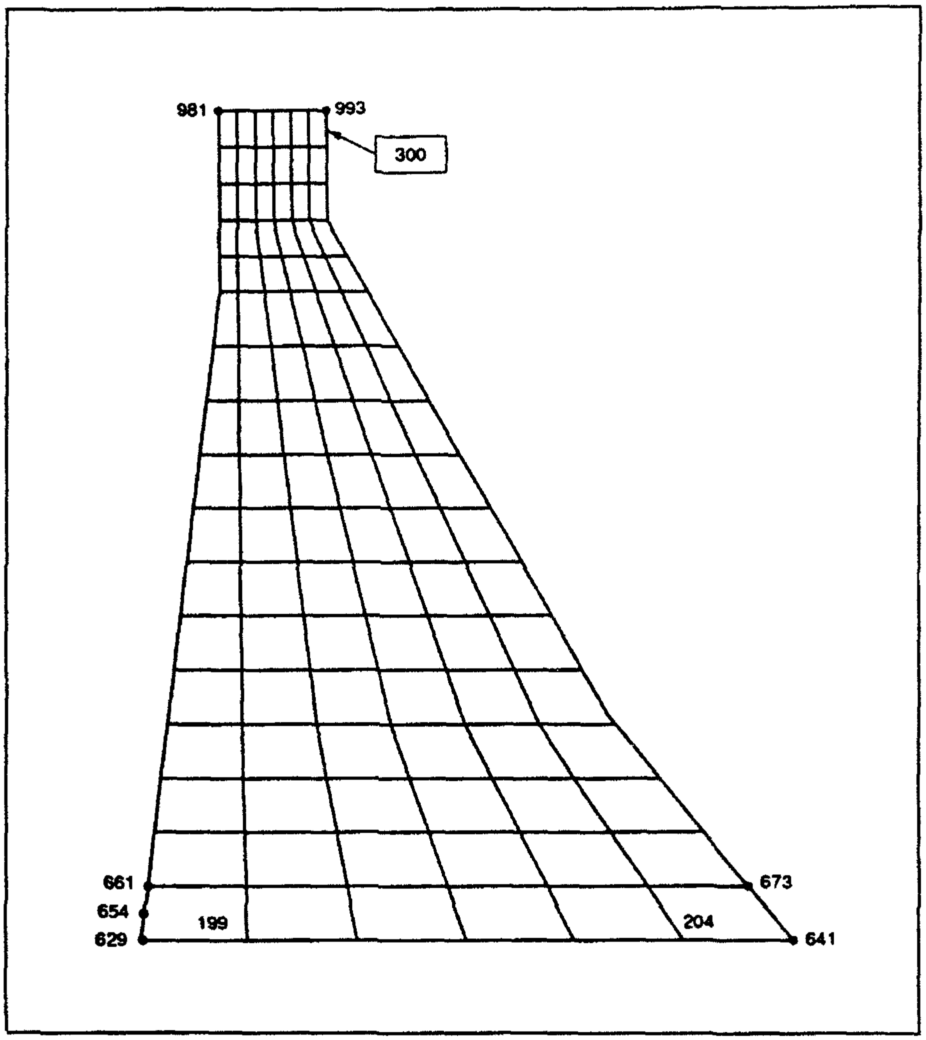



Figure 25. Six base-element model

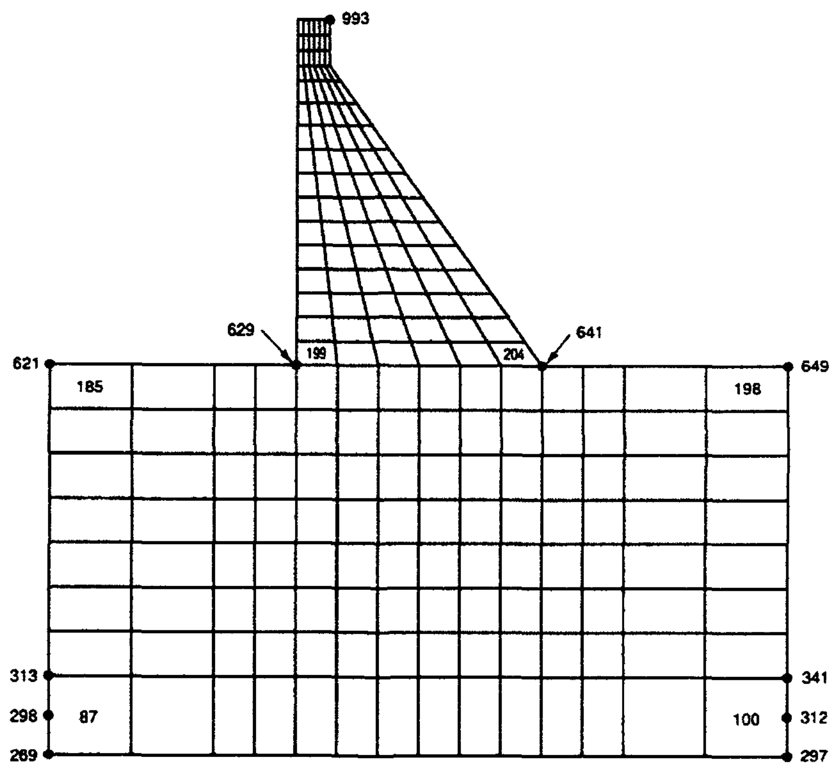



Figure 26. Mode' 1 (1.5-BW x 3-BW foundation model)

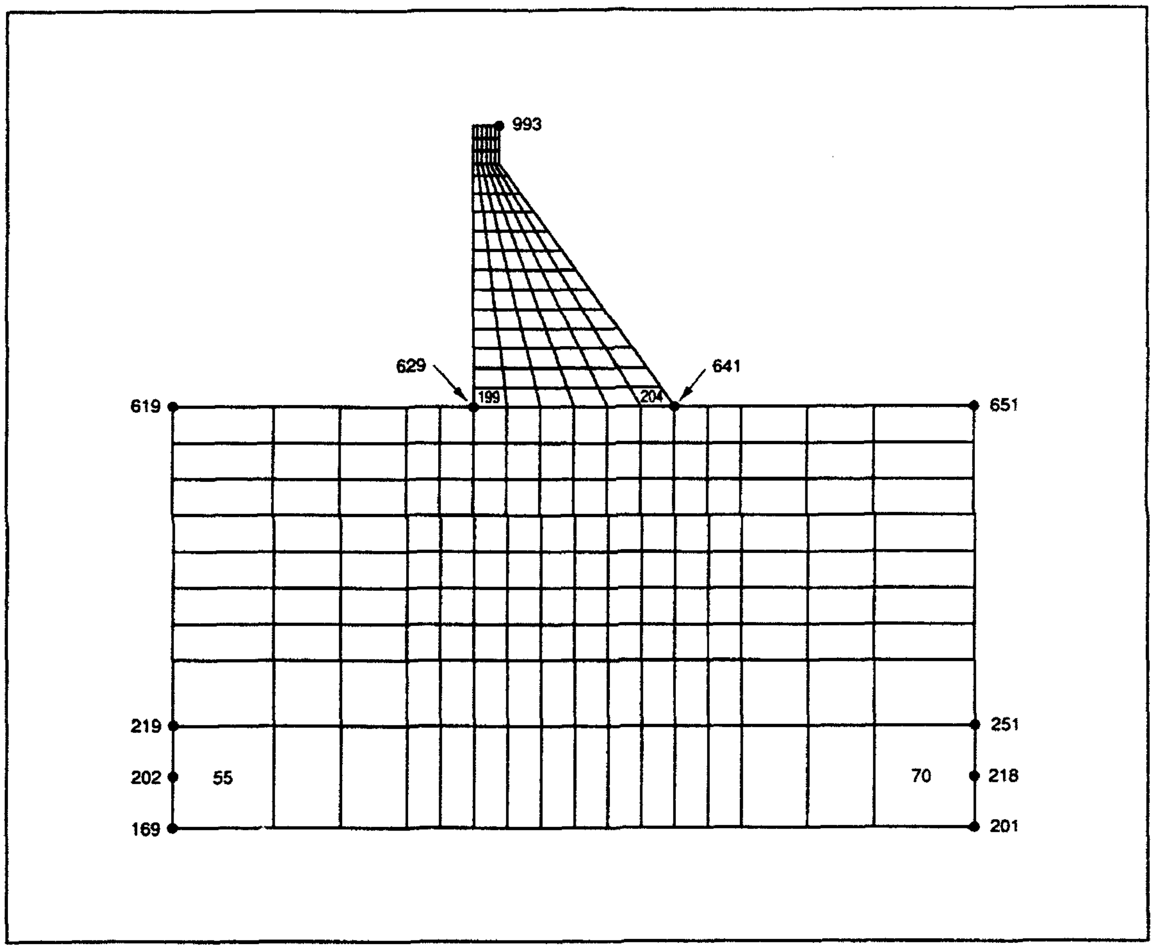



Figure 27. Model 2 (2-BW x 4-BW foundation model)

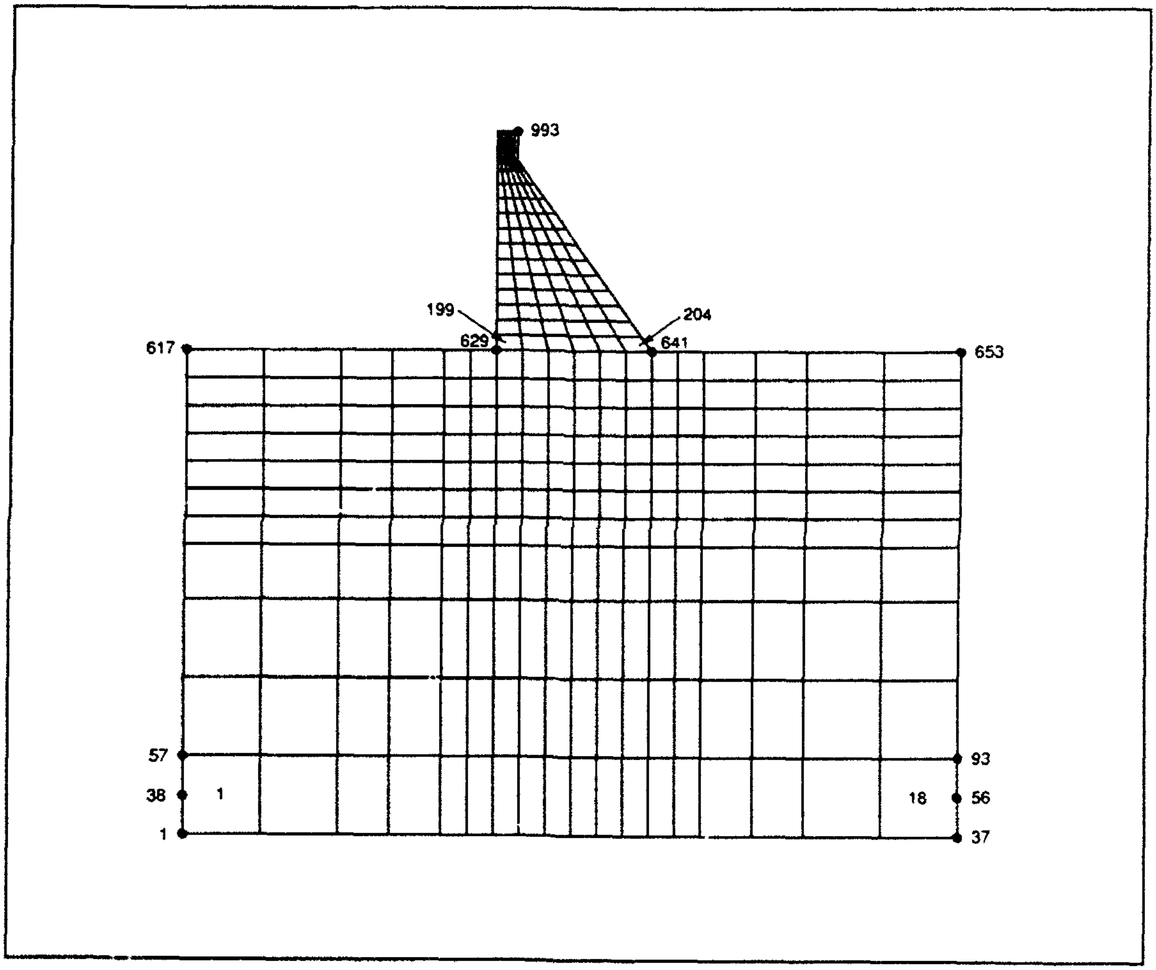



Figure 28. Model 3 (3-BW x 5-BW foundation model)

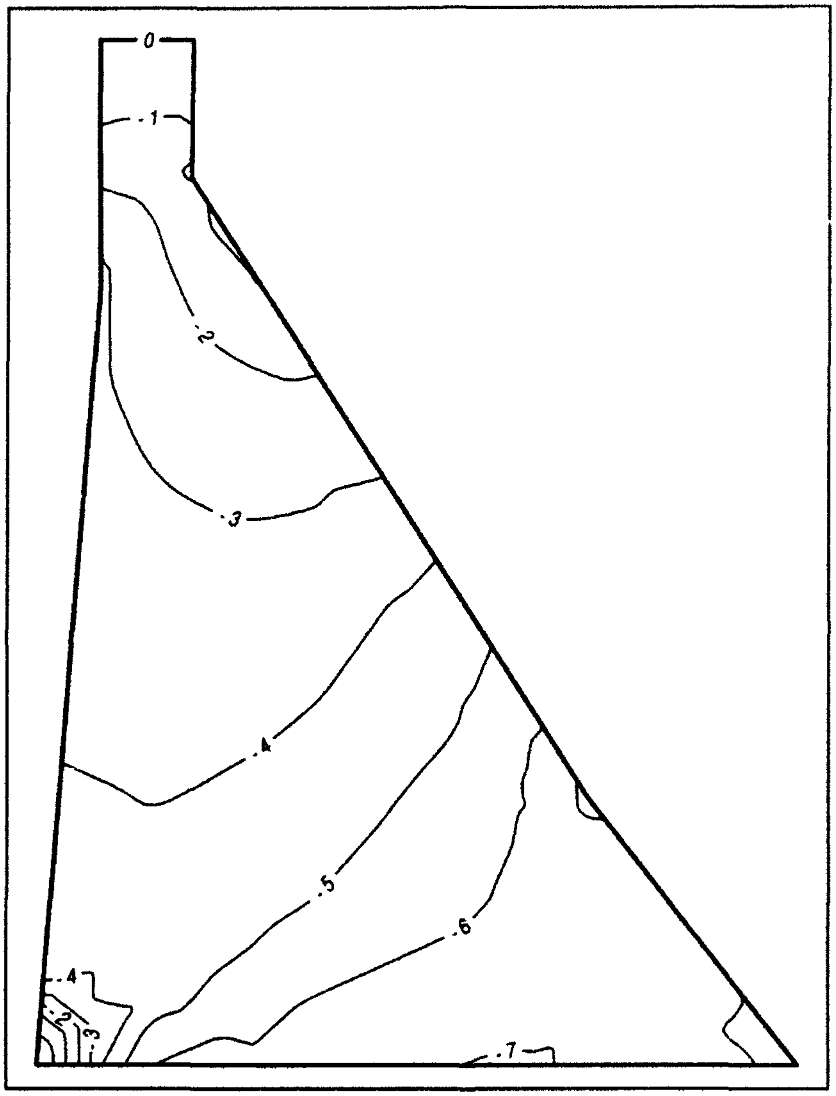



Figure 29. Vertical stresses (Syy), 3-BW x 5-BW foundation model


Figure 30. Horizontal stresses (Sxx), 3-BW x 5-BW foundation model

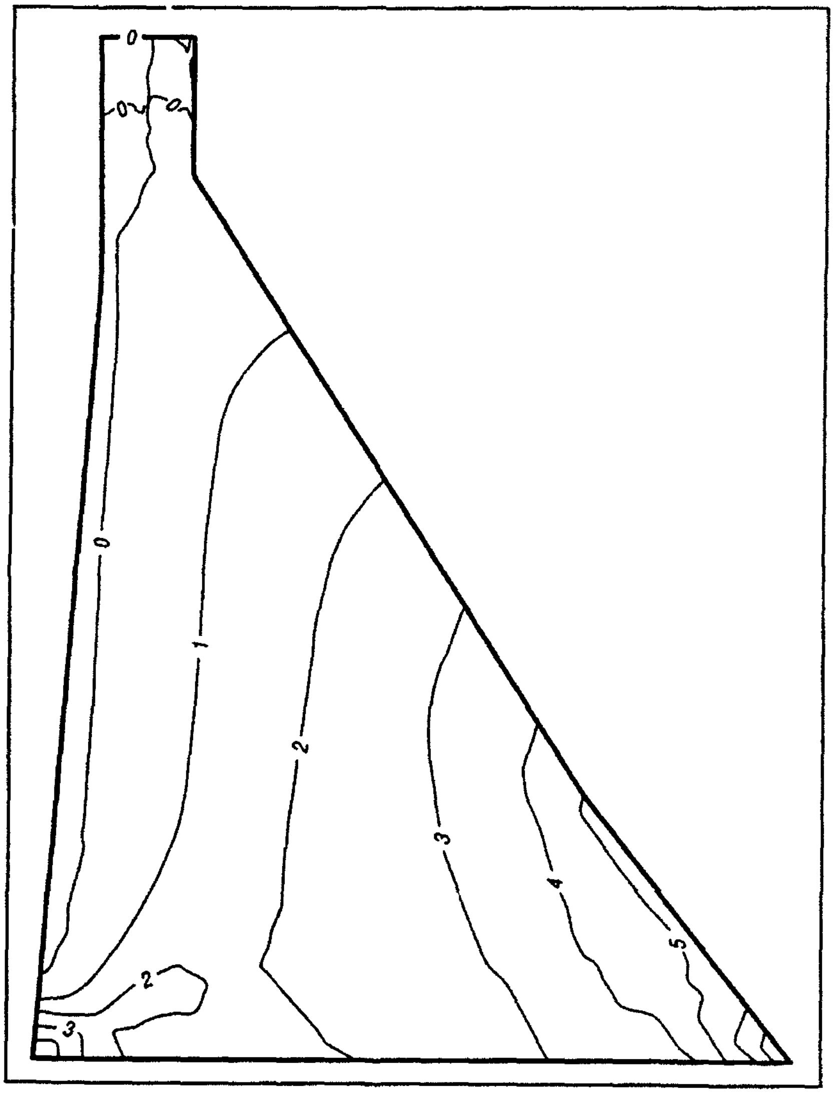



Figure 31. Shear stresses (Sxy), 3-BW x 5-BW foundation model

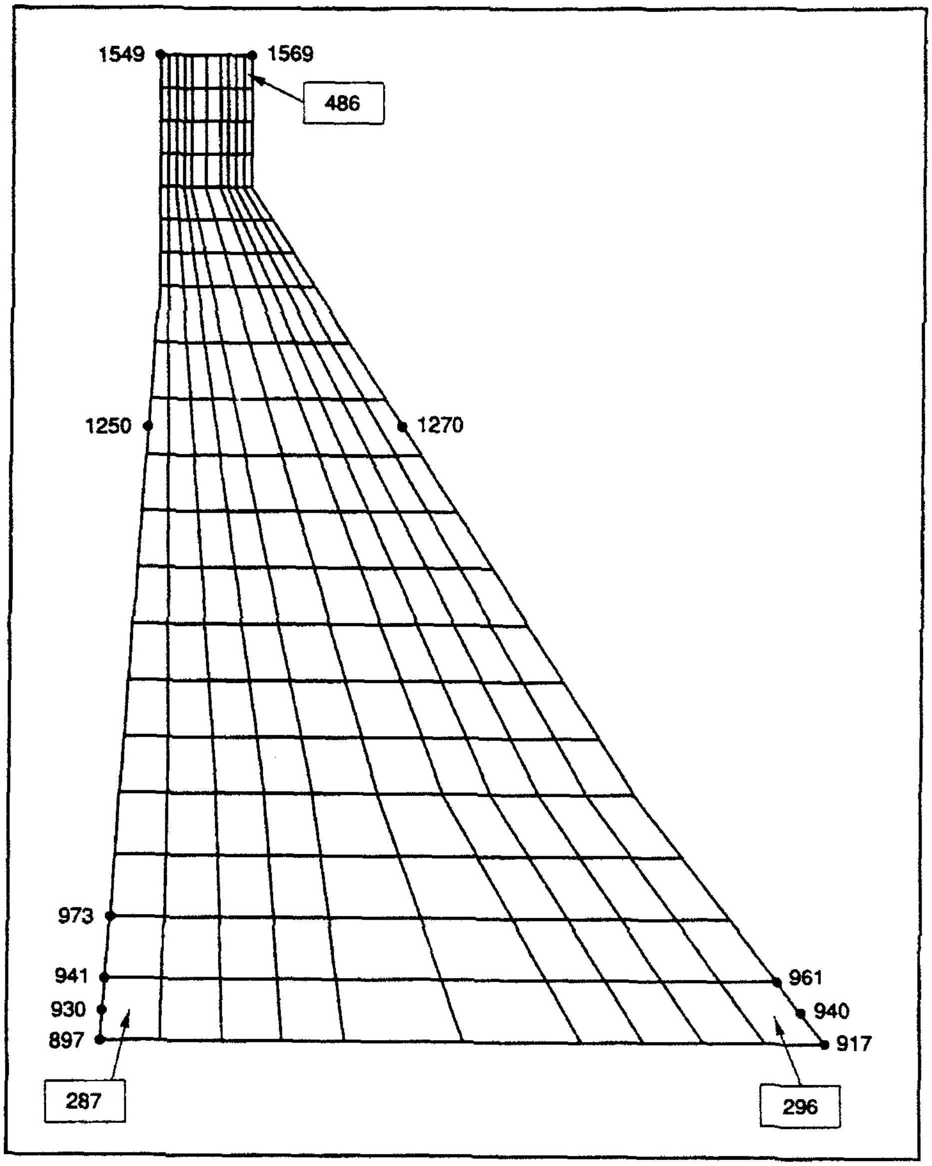



Figure 32. Ten base-element gravity dam model

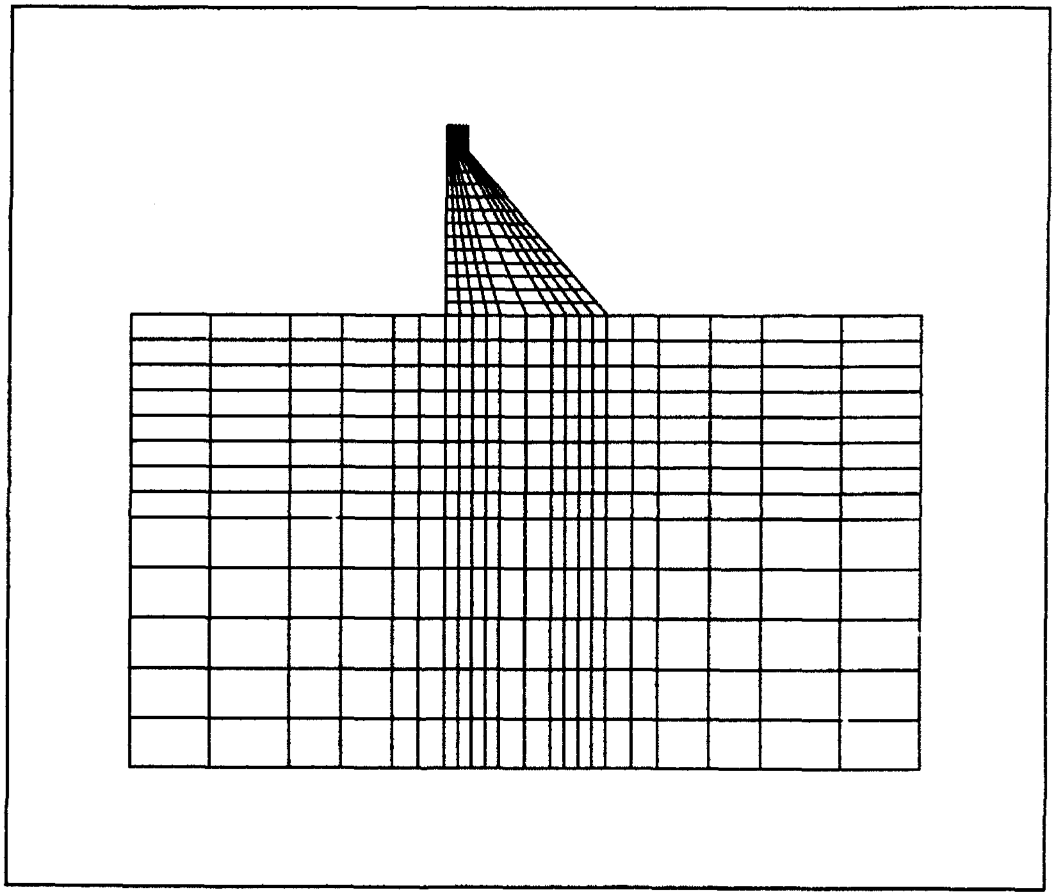


Figure 33. Dam-foundation model with 10 base elements

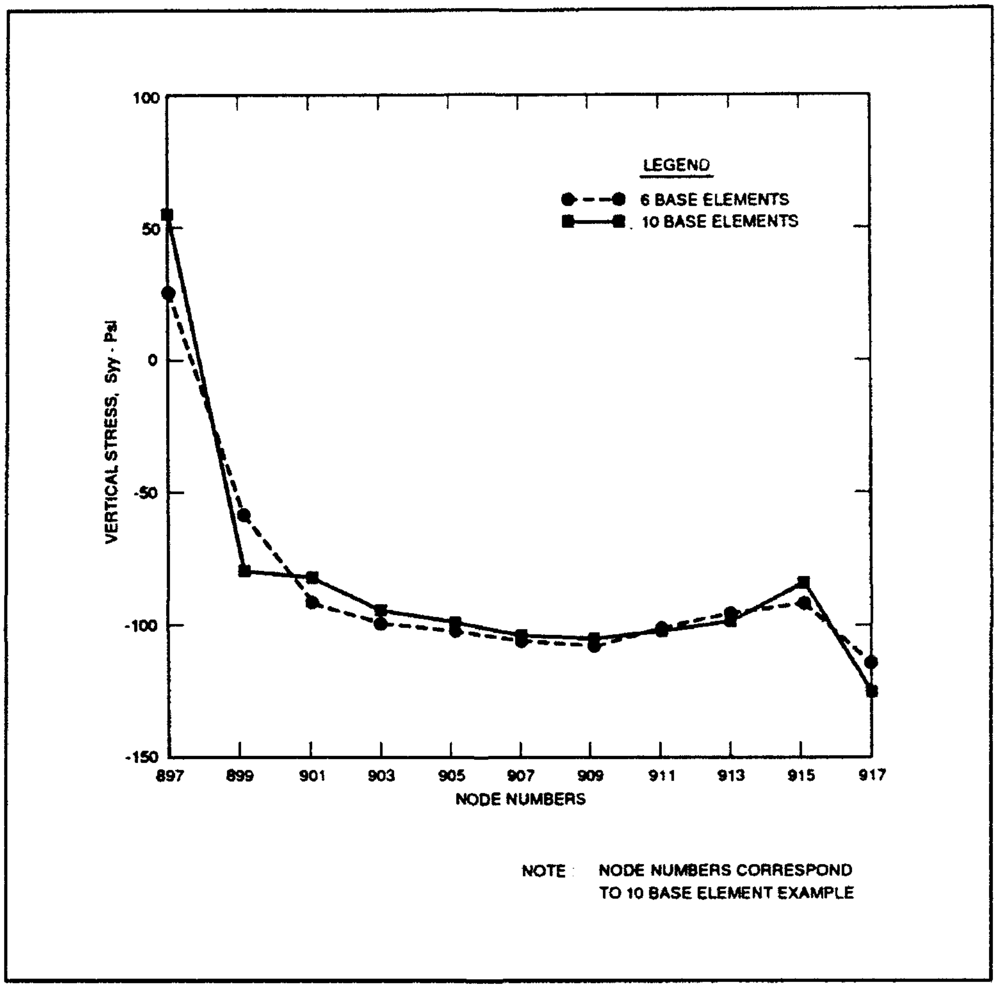



Figure 34. Change in vertical stresses versus change in mesh density

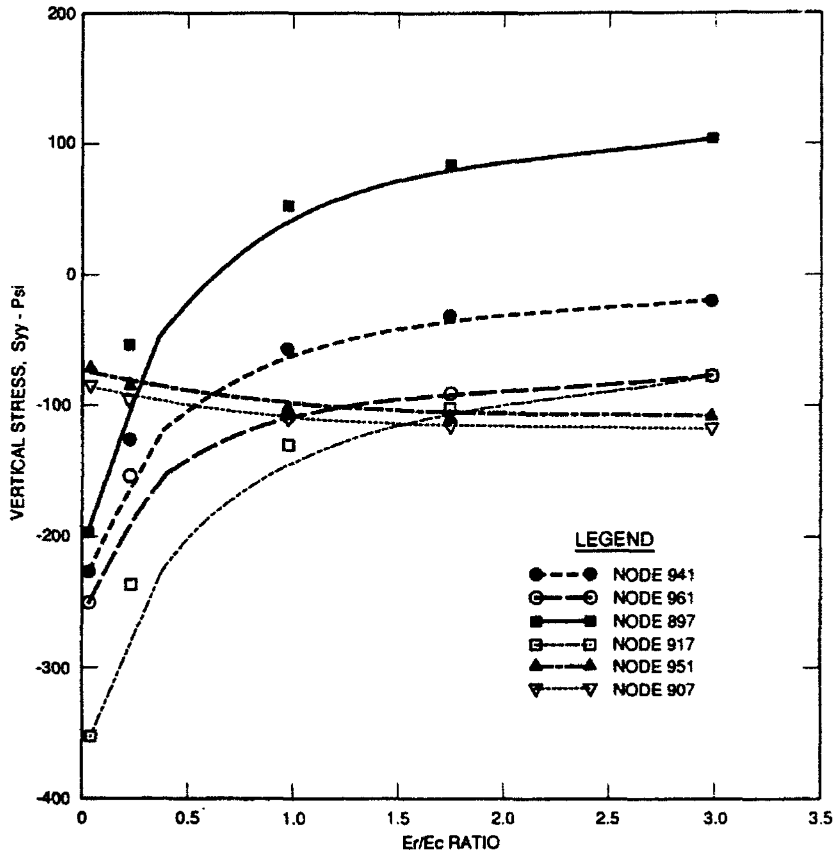



Figure 35. Foundation stiffness versus vertical stresses

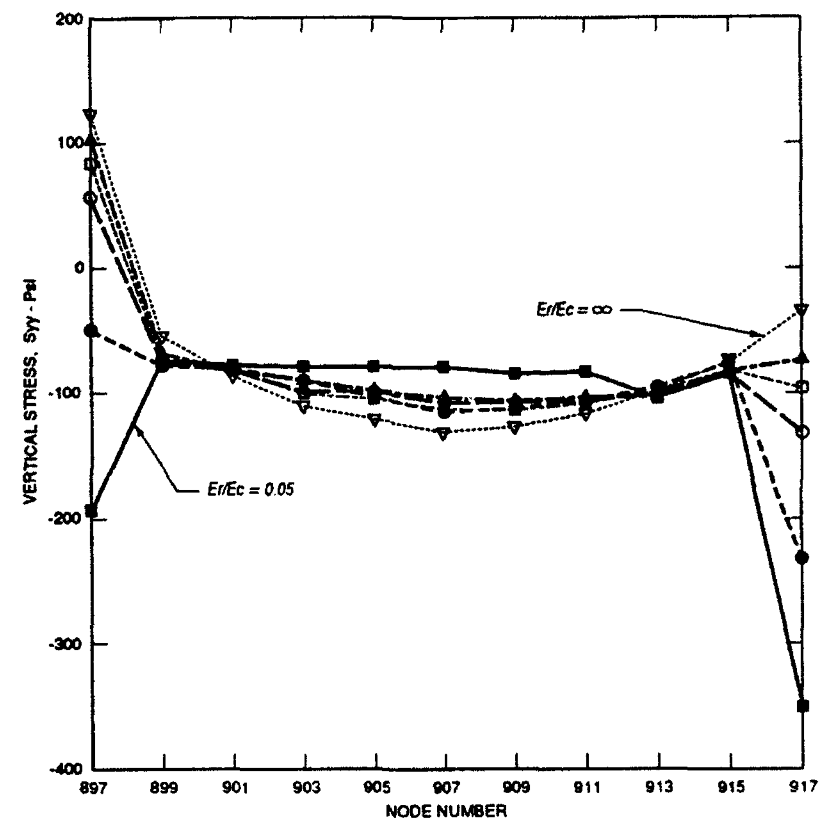



Figure 36. Vertical stresses versus foundation stiffness

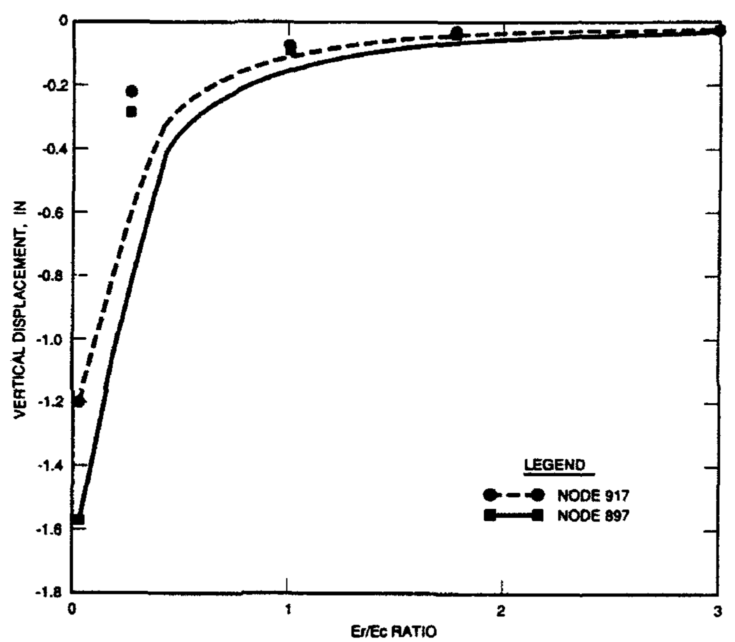



Figure 37. Vertical displacements versus foundation stiffness

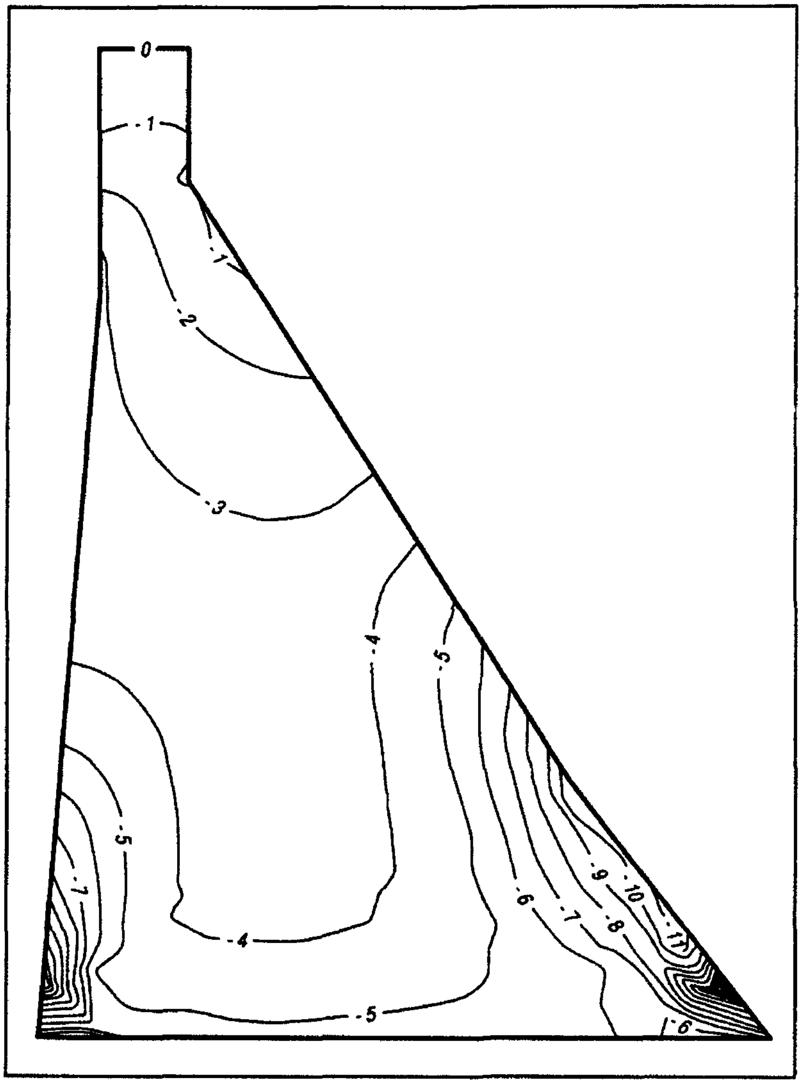



Figure 38. Er/Ec = 0.05, vertical stress contours

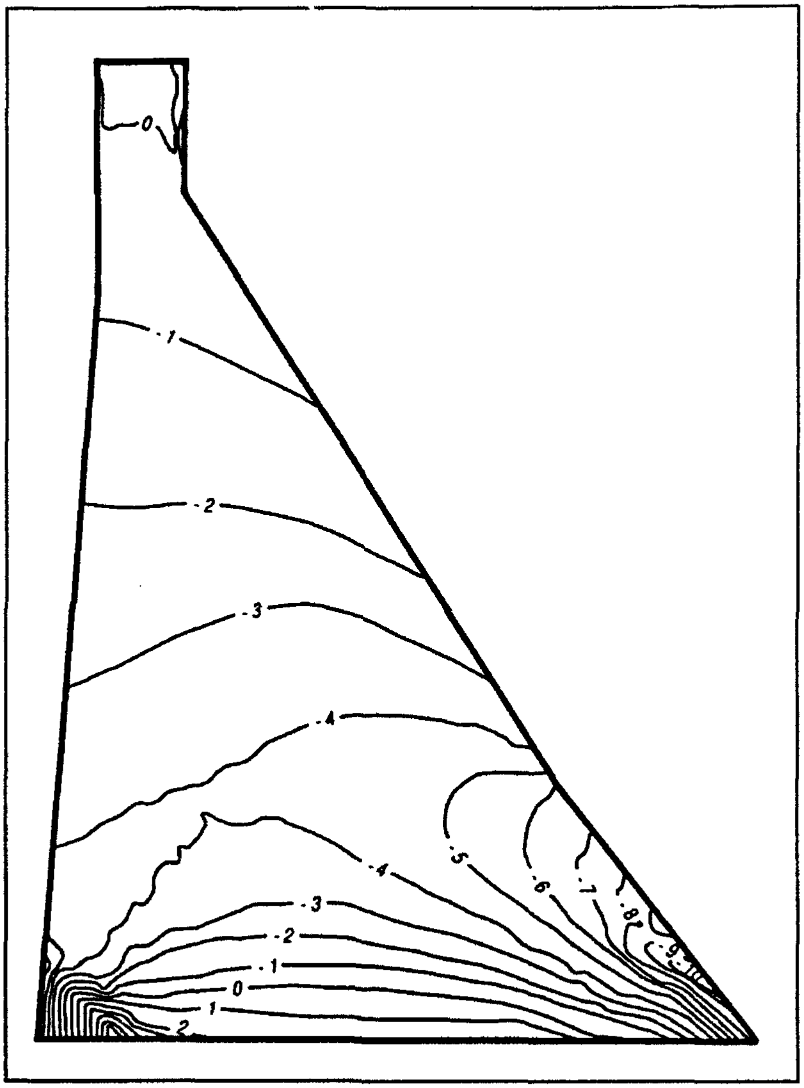



Figure 39. Er/Ec = 0.05, horizontal stress contours

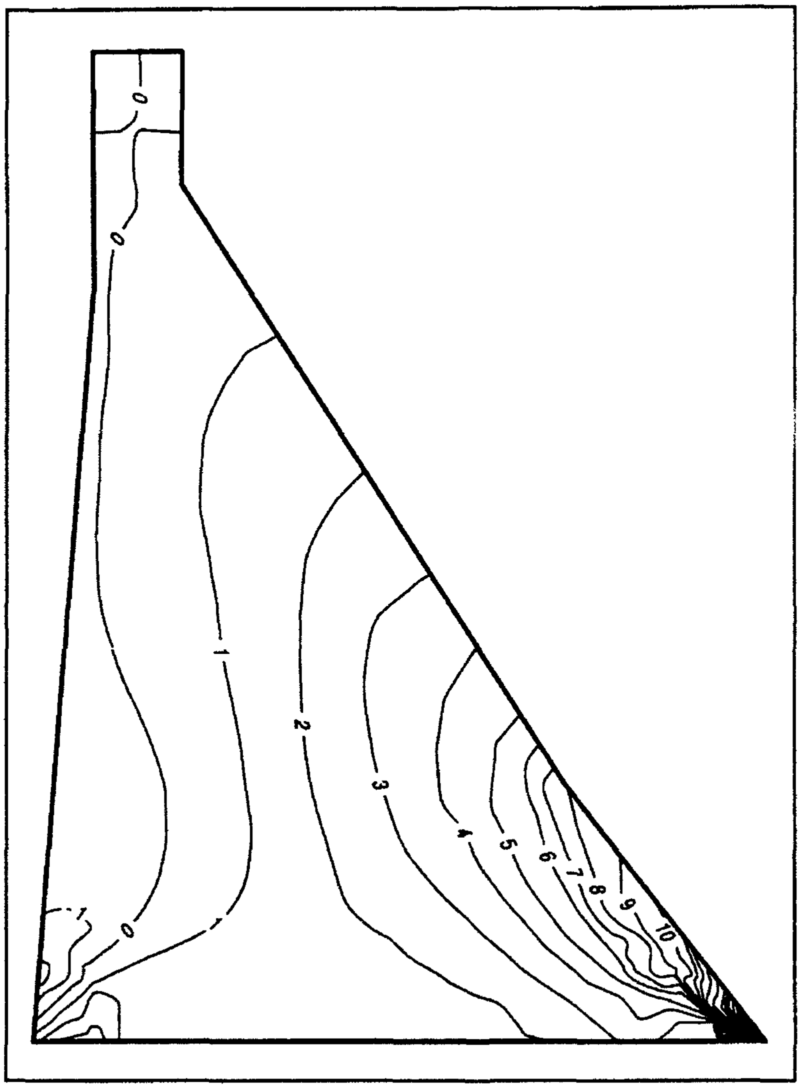



Figure 40. Er/Ec = 0.05, shear stress contours


Figure 41. Er/Ec = 0.25, vertical stress contours


Figure 42. Er/Ec = 0.25, horizontal stress contours

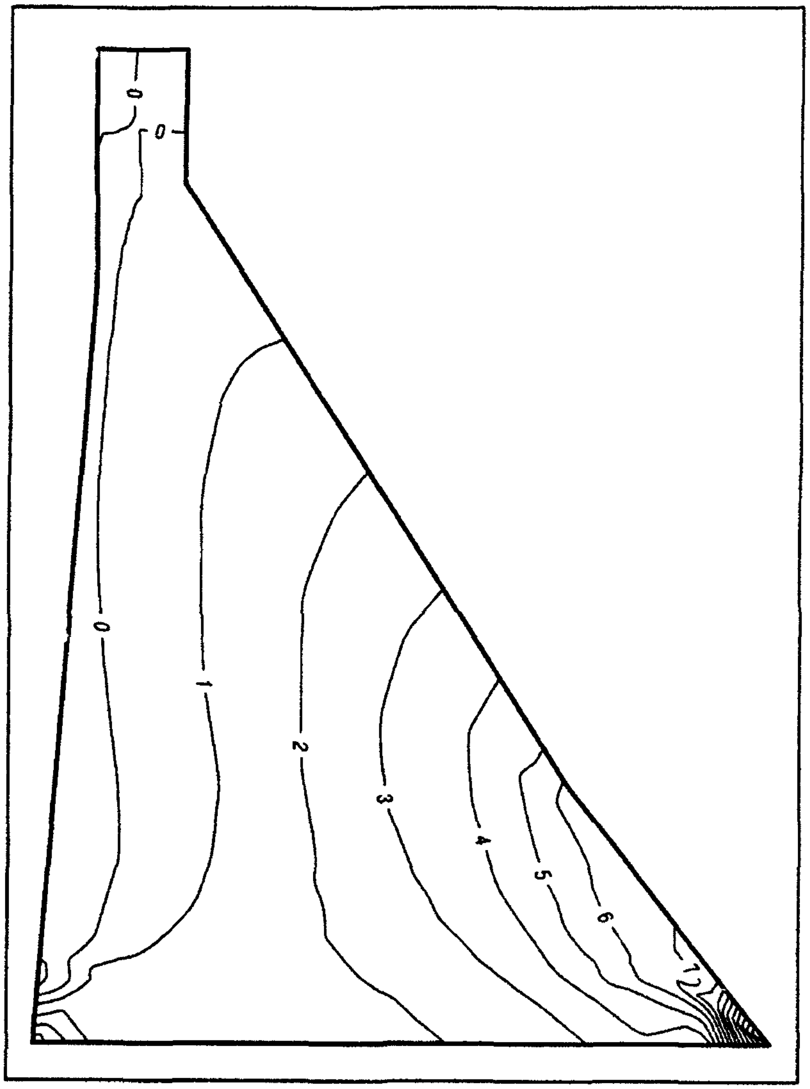



Figure 43. Er/Ec = 0.25, shear stress contours

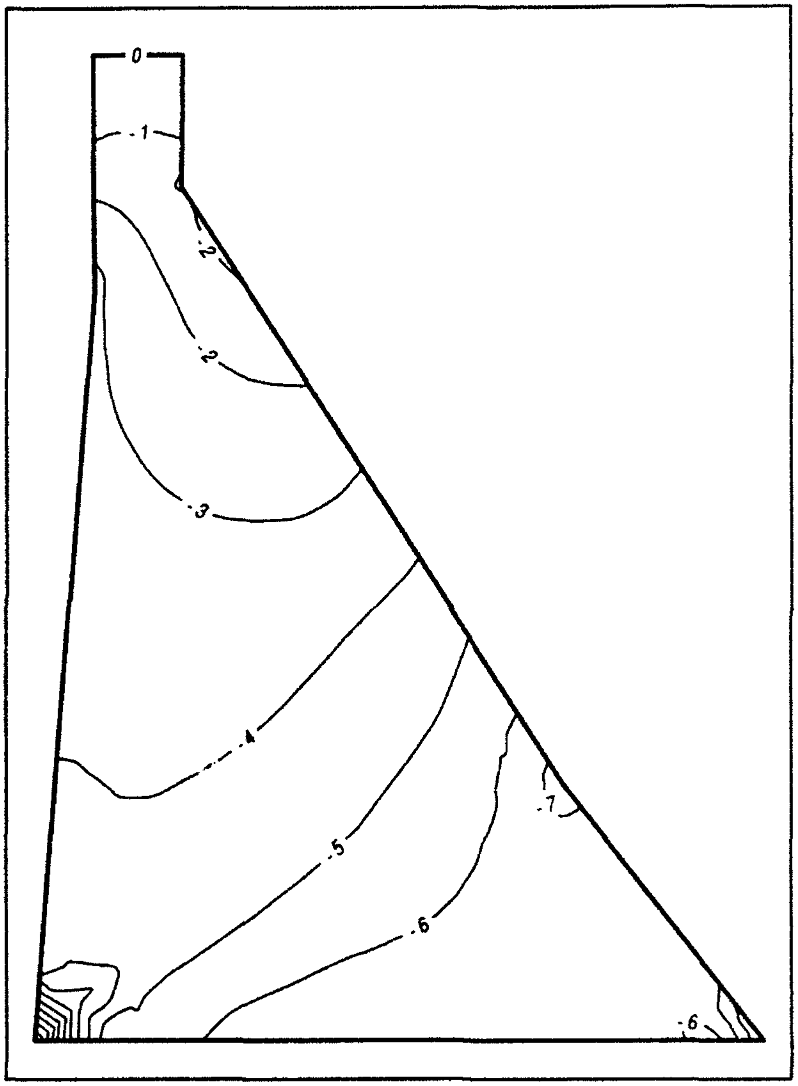



Figure 44.  Er/Ec = 1.00, vertical stress contours

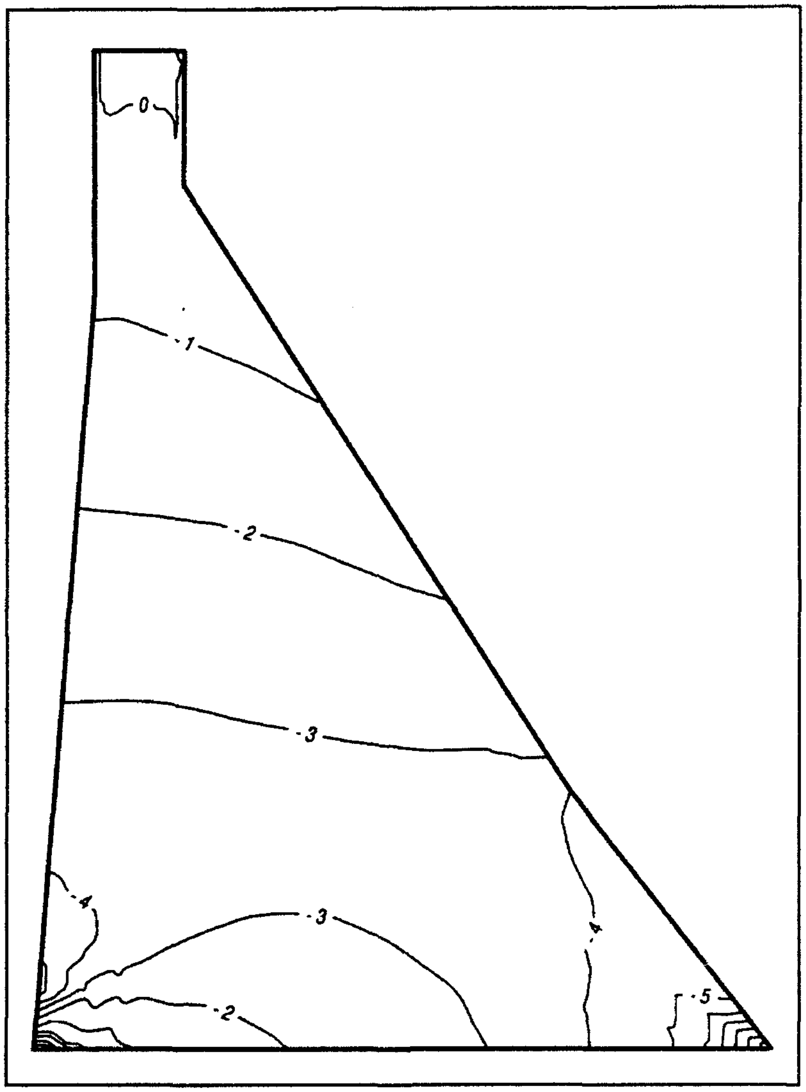



Figure 45. Er/Ec = 1.00, horizontal stress contours

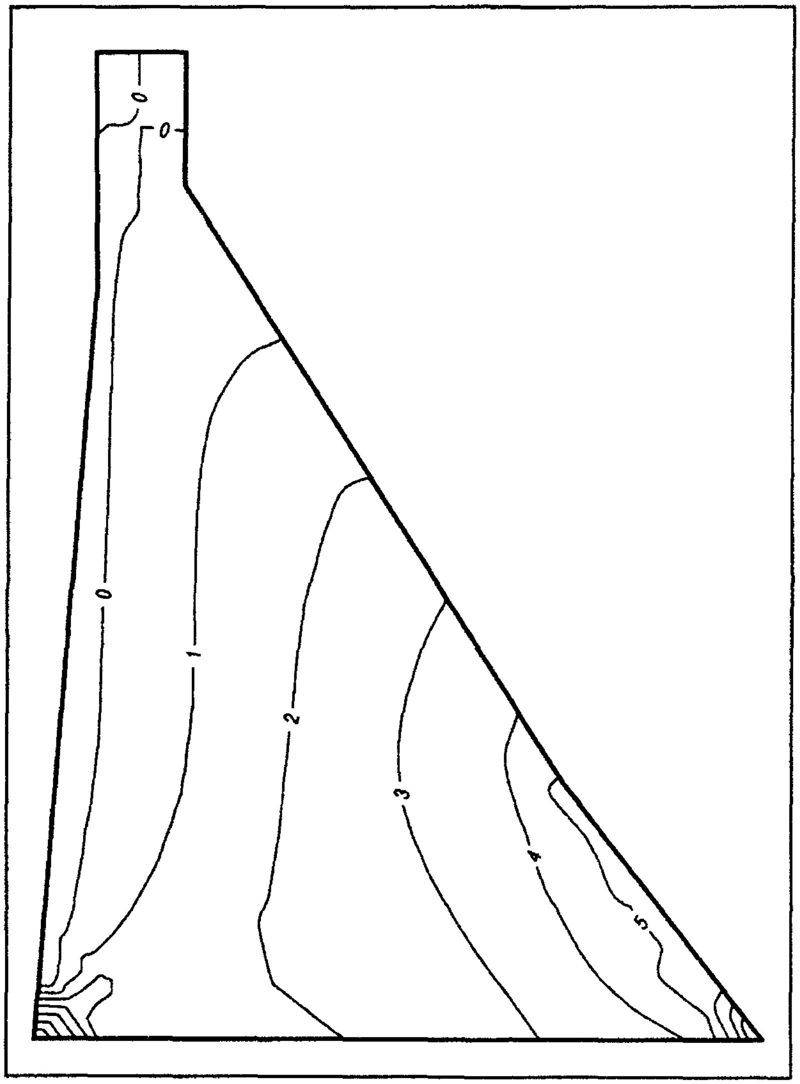



Figure 46. Er/Ec = 1.00, shear stress contours

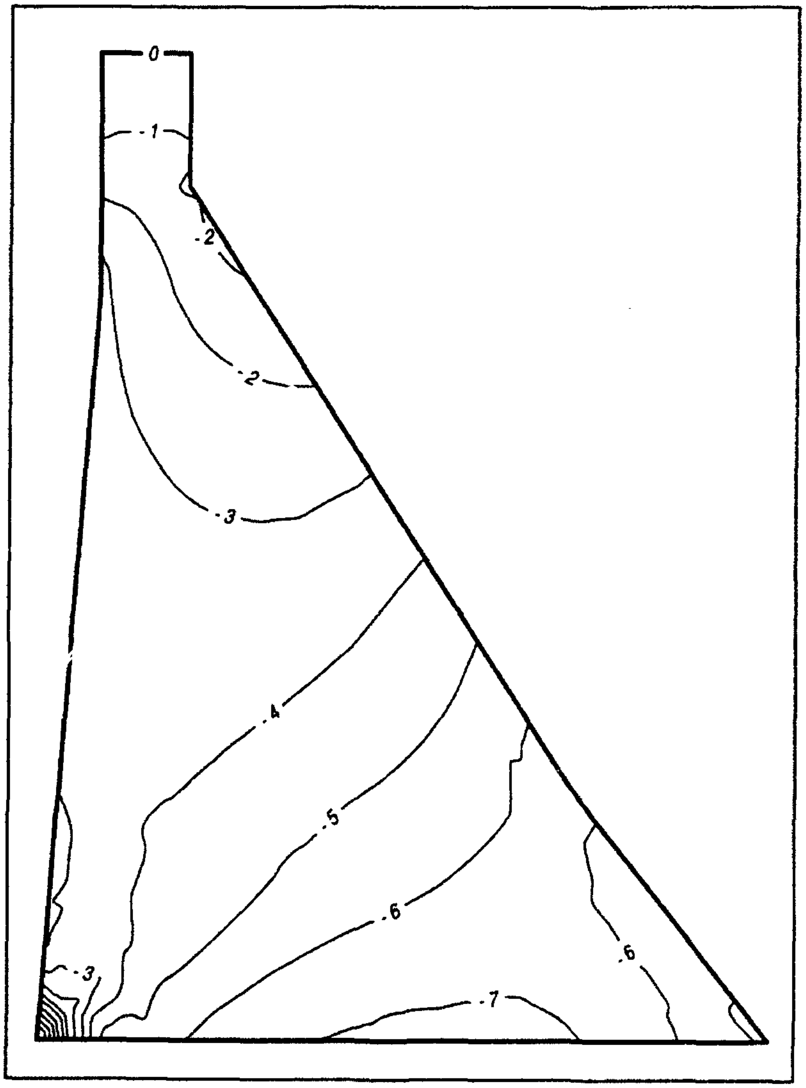



Figure 47. Er/Ec = 1.75, vertical stress contours


Figure 48.  Er/Ec = 1.75, horizontal stress contours

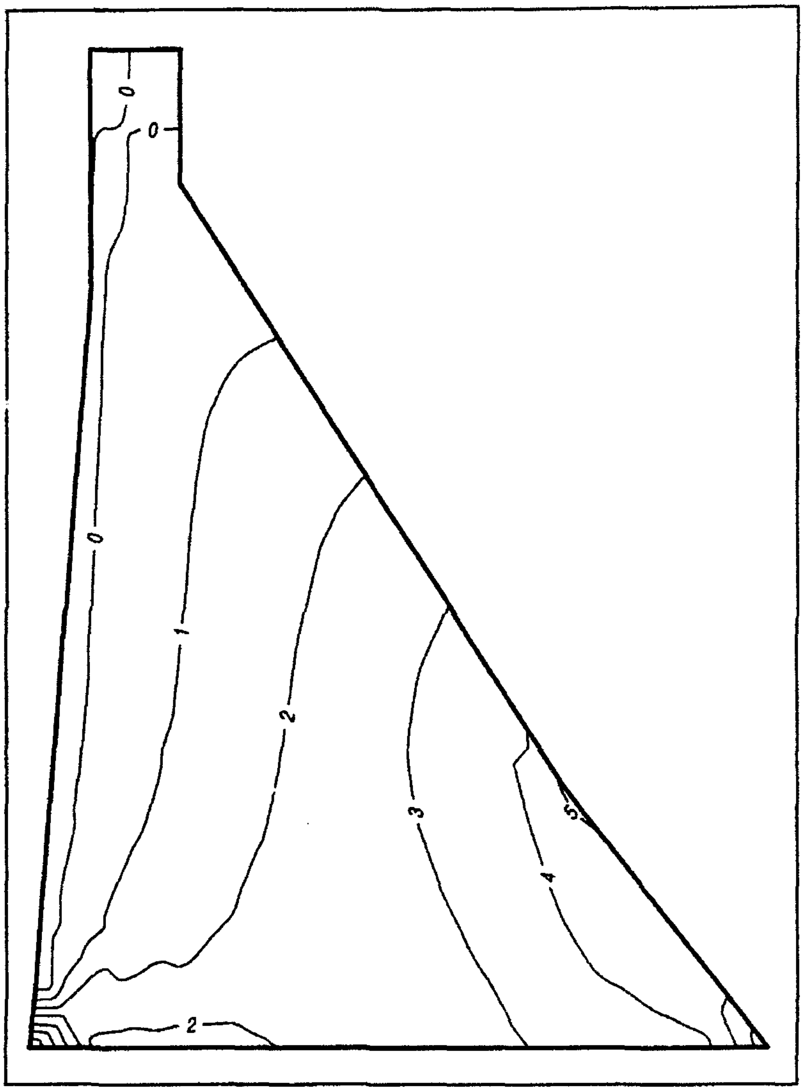



Figure 49. Er/Ec = 1.75, shear stress contours

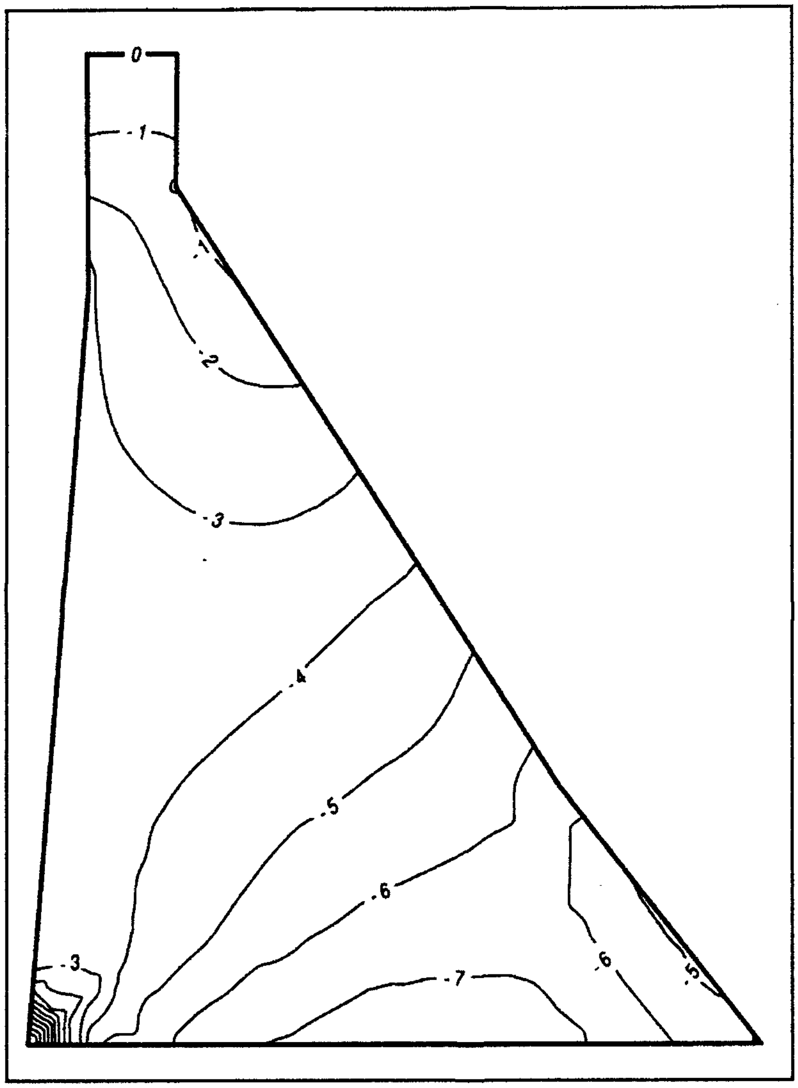



Figure 50. Er/Ec = 3.00, vertical stress contours

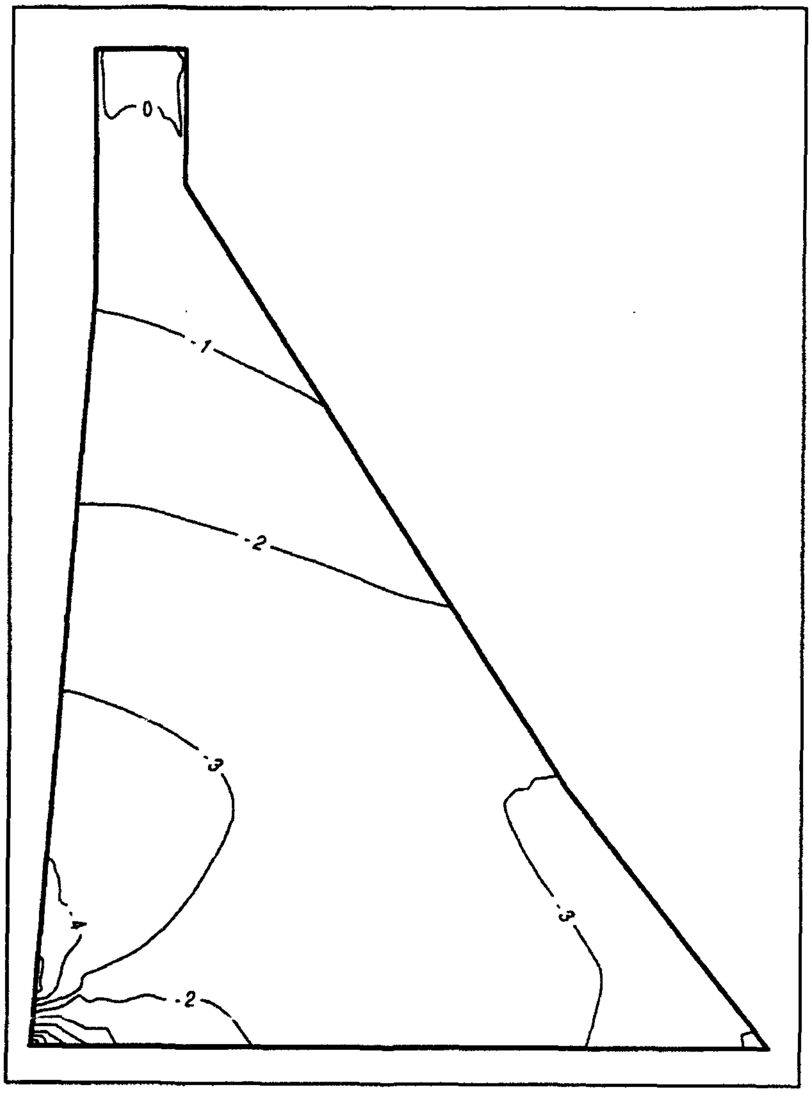



Figure 51. Er/Ec = 3.00, horizontal stress contours

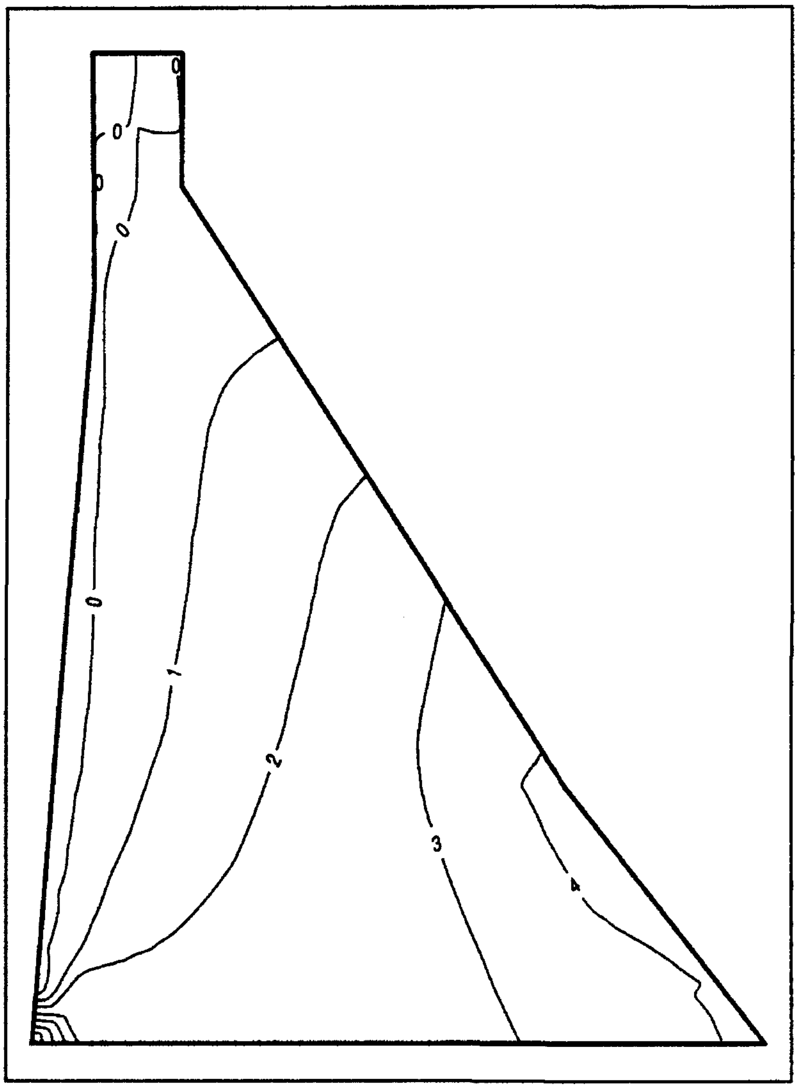



Figure 52. Er/Ec = 3.00, shear stress contours

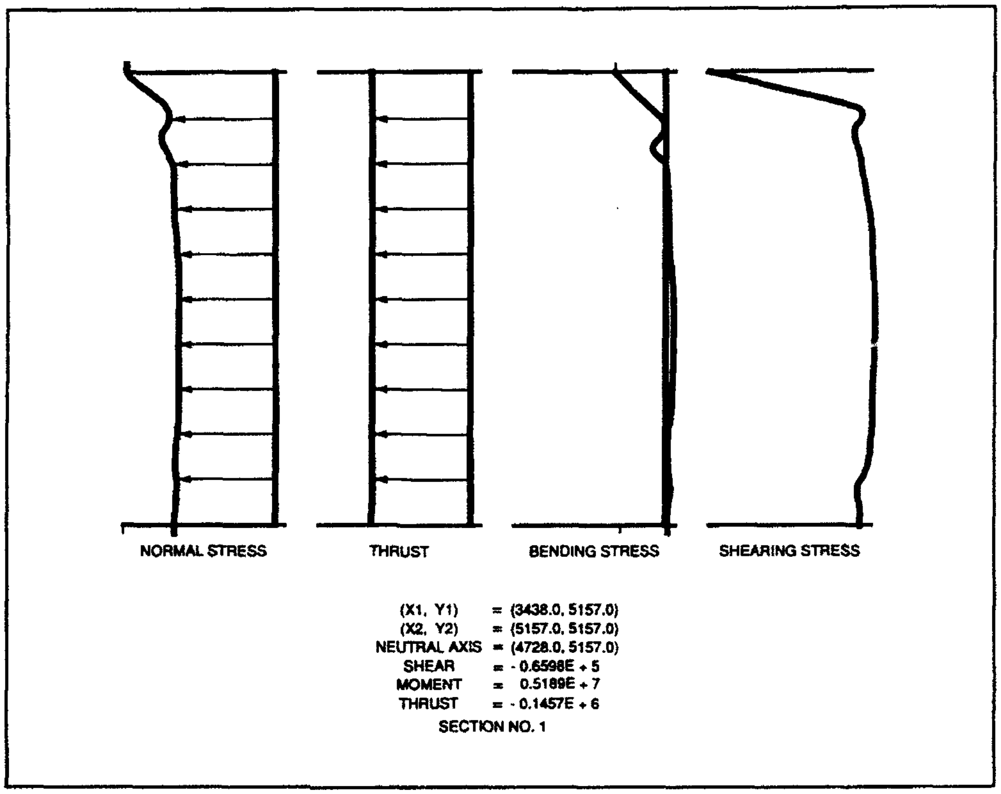



Figure 53. Er/Ec = 0.05, CSMT plots

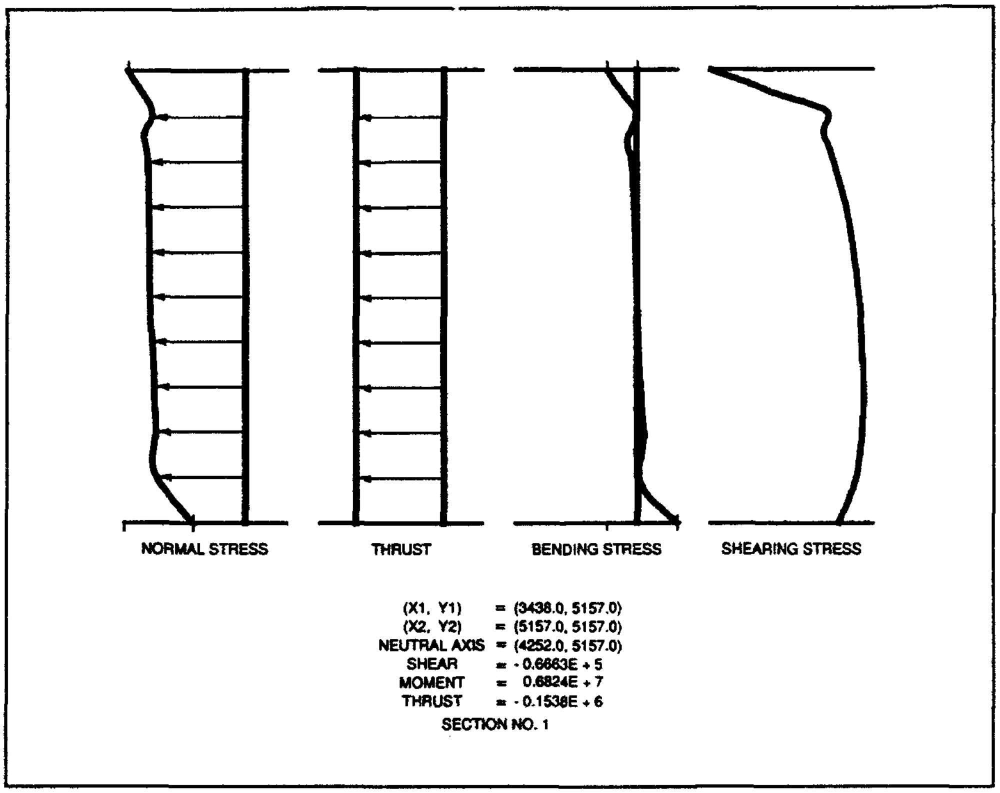



Figure 54. Er/Ec = 0.25, CSMT plots

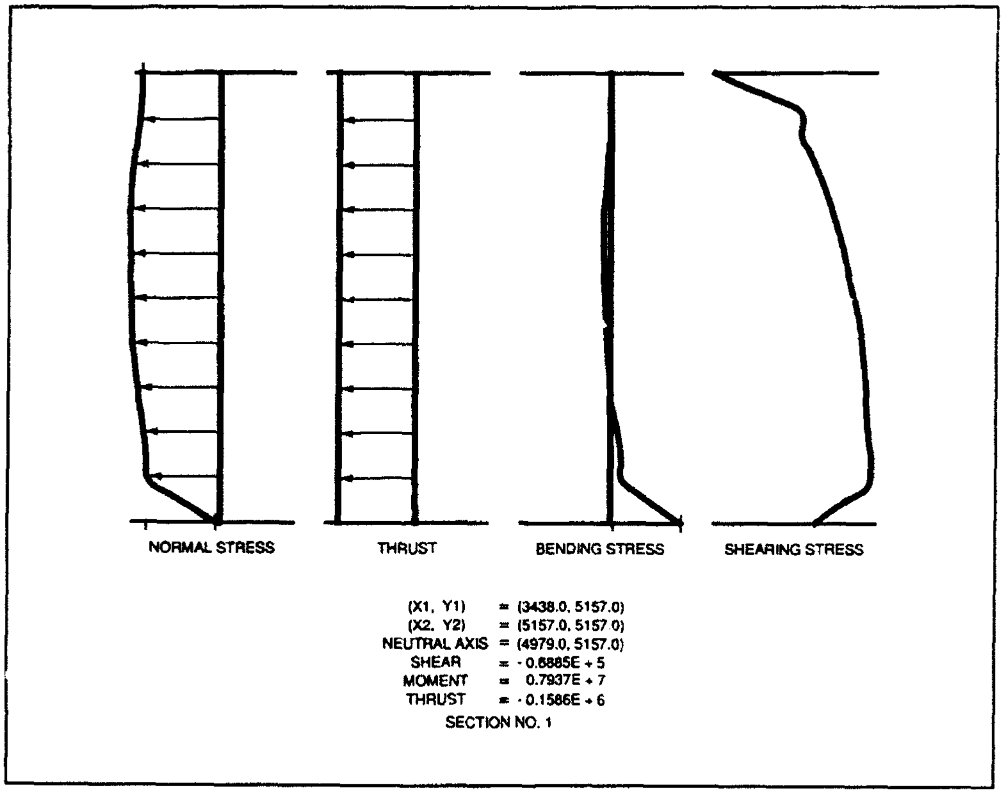



Figure 55. Er/Ec = 1.00, CSMT plots

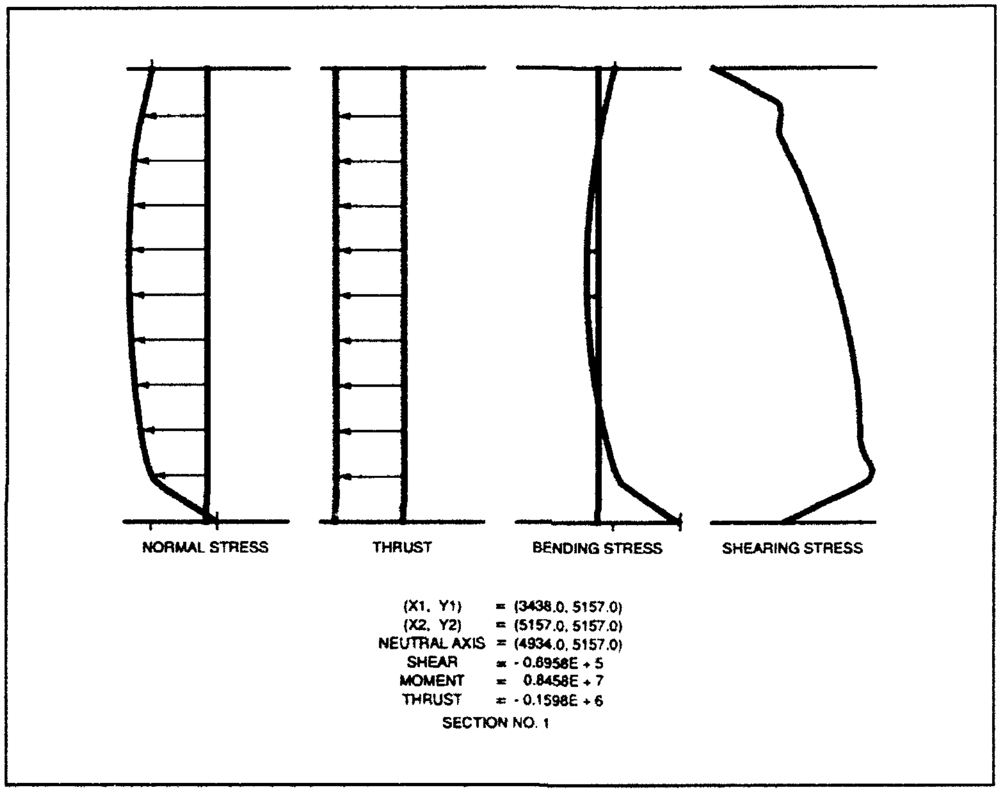



Figure 56. Er/Ec = 1.75, CSMT plots

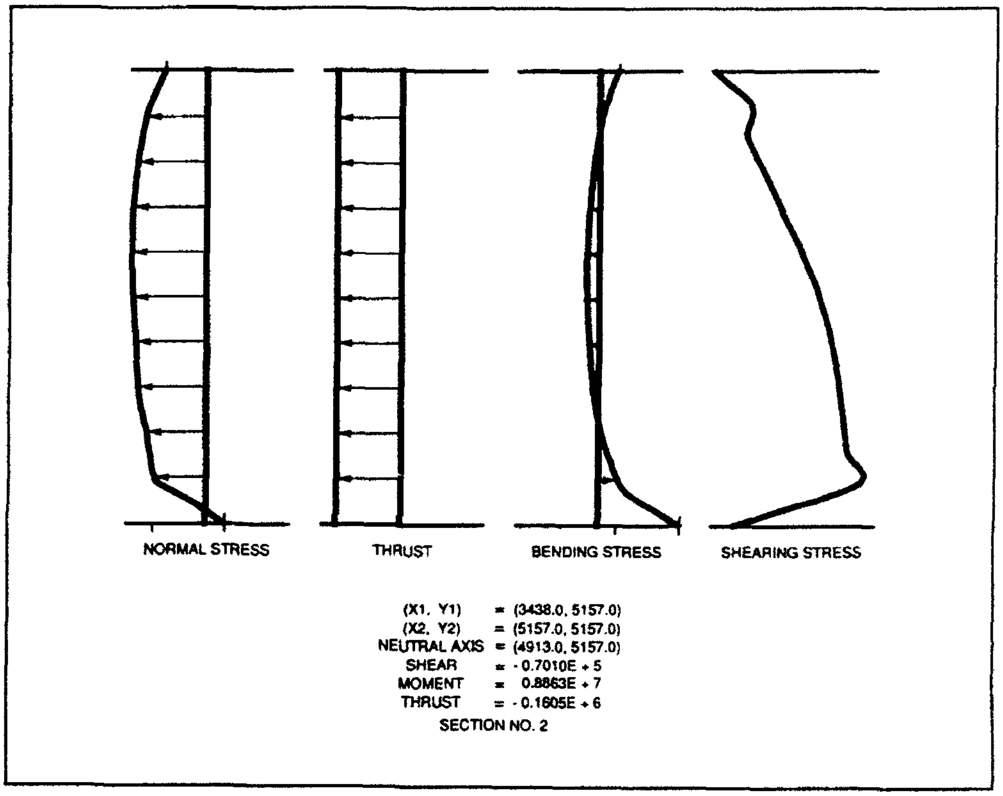



Figure 57. Er/Ec = 3.00, CSMT plots

**Table 1**
**Dimensions of Models**

| Model Number | Width of Foundation Model (BW) | Depth of Foundation Model (BW) |
|---|---|---|
| 1 | 3 | 1 |
| 2 | 3 | 2 |
| 3 | 5 | 2 |
| 4 | 5 | 3 |
| 5 | 7 | 3 |
| 6 | 7 | 4 |
| 7 | 9 | 4 |
| 8 | 9 | 5 |
| 9 | 11 | 5 |
| 10 | 11 | 6 |

Note: All dimensions are given in terms of the base width (BW) of the applied pressure load. Model 1 would have a depth of 1 BW and a total of 3 BW.

**Table 2**
**Tabulations of Finite Element and Closed Form Stress Results for Uniform Normal Pressure Load**

| Point | T.O.E. | MD2 | MD3 | MD4 | MD5 | MD6 | MD7 | MD8 |
|---|---|---|---|---|---|---|---|---|
| | | | | $\sigma_{xx}$ | | | | |
| 1 | -1000.0 | -861.1 | -888.3 | -929.4 | -938.8 | -959.1 | -963.8 | -975.9 |
| 2 | -742.9 | -577.8 | -594.0 | -628.3 | -635.1 | -653.0 | -656.7 | -667 7 |
| 3 | -493.2 | -350.9 | -356.8 | -386.0 | -390.4 | -406.4 | -409.2 | -419.3 |
| 4 | -321.4 | -230.9 | -225.8 | -250.6 | -252.4 | -266.8 | -268.6 | -277.8 |
| 5 | -251.8 | -184.2 | -167.2 | -188.3 | -187.4 | -200.1 | -200.9 | -209.4 |
| 6 | -225.0 | -172.4 | -143.0 | -160.9 | -157.1 | -168.4 | -168.2 | -175.9 |
| 7 | -206.2 | -172.9 | -132.6 | -147.8 | -140.8 | -150.9 | -149.5 | -156.6 |
| 8 | -188.9 | -181.9 | -126.7 | -139.3 | -129.2 | -138.2 | -135.6 | -142.1 |
| 9 | -172.8 | -190.3 | -122.8 | -133.1 | -119.6 | -127.6 | -123.9 | -129.8 |
| 10 | -158.4 | -199.1 | -120.6 | -128.5 | -111.6 | -118.7 | -113.6 | -119.1 |
| 11 | -145.7 | -207.5 | -119.9 | -125.4 | -105.0 | -111.3 | -103.2 | -108.4 |

*(Continued)*

| Table 2 (Concluded) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Point | T.O.E. | MD2 | MD3 | MD4 | MD5 | MD6 | MD7 | MD8 |
| | | | | $\sigma_{yy}$ | | | | |
| 1 | -1000.0 | -1072.0 | -1075.4 | -1076.9 | -1077.8 | -1078.3 | -1079.1 | -1079.2 |
| 2 | -996.0 | -981.7 | -982.3 | -981.5 | -981.7 | -981.5 | -981.5 | -981.5 |
| 3 | -955.2 | -937.6 | -938.7 | -937.2 | -937.4 | -937.0 | -937.1 | -936.9 |
| 4 | -824.5 | -826.1 | -827.8 | -825.1 | -825.6 | -824.9 | -825.1 | -824.8 |
| 5 | -637.8 | -641.4 | -643.6 | -639.6 | -640.4 | -639.2 | -639.5 | -639.0 |
| 6 | -479.7 | -482.1 | -484.3 | -478.9 | -480.0 | -478.4 | -478.8 | -478.1 |
| 7 | -370.6 | -374.7 | -376.1 | -369.5 | -370.8 | -368.7 | -369.2 | -368.3 |
| 8 | -297.8 | -305.4 | -304.8 | -297.3 | -298.9 | -296.2 | -296.9 | -295.8 |
| 9 | -247.6 | -260.5 | -255.8 | -248.2 | -249.9 | -246.8 | -247.6 | -246.2 |
| 10 | -211.7 | -231.4 | -220.4 | -213.2 | -214.9 | -211.5 | -212.4 | -210.8 |
| 11 | -184.8 | -213.5 | -193.2 | -187.4 | -188.9 | -185.2 | -223.1 | -221.2 |
| | | | | $\tau_{xy}$ | | | | |
| 1 | 0 | 39.2 | 40.7 | 41.8 | 42.1 | 42.5 | 42.6 | 42.8 |
| 2 | 10.1 | 12.9 | 12.4 | 13.0 | 12.9 | 13.0 | 13.0 | 13.7 |
| 3 | 73.9 | 76.3 | 74.8 | 77.0 | 76.6 | 77.2 | 77.1 | 77.3 |
| 4 | 191.1 | 175.9 | 173.1 | 177.8 | 177.0 | 178.3 | 177.9 | 178.5 |
| 5 | 247.0 | 232.9 | 229.2 | 236.9 | 235.6 | 237.7 | 237.2 | 238.0 |
| 6 | 254.6 | 237.4 | 233.3 | 244.5 | 242.3 | 245.9 | 245.2 | 246.4 |
| 7 | 236.7 | 216.6 | 213.4 | 228.3 | 225.9 | 230.3 | 229.4 | 231.0 |
| 8 | 213.5 | 187.9 | 186.7 | 205.6 | 202.9 | 208.5 | 207.4 | 209.5 |
| 9 | 191.6 | 158.0 | 160.4 | 183.2 | 180.3 | 187.2 | 185.8 | 188.6 |
| 10 | 172.7 | 128.9 | 136.3 | 162.9 | 159.9 | 168.2 | 166.7 | 169.9 |
| 11 | 156.7 | 101.2 | 114.5 | 144.8 | 141.9 | 151.6 | 158.6 | 162.2 |

**Table 3**
**Tabulations of Finite Element and Closed Form Stress Results for Uniform Shear Load**

| Point | T.O.E. | MDC1 | MDC2 | MDC3 | MDC4 | MDC5 |
|---|---|---|---|---|---|---|
| | | | $\sigma_{xx}$ | | | |
| 1 | 0 | 0 | 0 | 0 | 0 | 0.0 |
| 2 | -237.4 | -238.2 | -367.2 | -355.0 | -360.2 | -357.5 |
| 3 | -373.4 | -354.7 | -367.2 | -355.0 | -360.2 | -357.5 |
| 4 | -368.1 | -349.6 | -358.3 | -340.4 | -346.7 | -342.6 |
| 5 | -307.3 | -318.4 | -318.2 | -295.9 | -302.5 | -296.9 |
| 6 | -257.7 | -293.8 | -278.3 | -253.3 | -259.5 | -252.7 |
| 7 | -233.3 | -281.1 | -246.4 | -221.3 | -226.5 | -218.5 |
| 8 | -197.9 | -282.2 | -220.8 | -198.6 | -202.1 | -193.2 |
| 9 | -177.8 | -293.9 | -198.1 | -182.2 | 183.4 | -174.0 |
| 10 | -161.3 | -314.6 | -176.2 | -170.3 | -168.6 | -158.9 |
| 11 | -147.4 | -342.7 | -154.1 | -161.6 | -156.1 | -146.8 |
| | | | $\sigma_{yy}$ | | | |
| 1 | 0 | 0 | 0 | 0 | 0 | 0.0 |
| 2 | -10.1 | -20.7 | -20.1 | -19.9 | -19.9 | -19.9 |
| 3 | -73.9 | -71.2 | -68.9 | -68.1 | -67.9 | -67.8 |
| 4 | -181.1 | -171.9 | -166.1 | -163.9 | -163.4 | -163.1 |
| 5 | -247.1 | -251.3 | -239.9 | -235.2 | -234.2 | -233.6 |
| 6 | -254.6 | -275.0 | -258.0 | -249.2 | -247.4 | -246.3 |
| 7 | -236.7 | -273.6 | -251.3 | -236.7 | -233.9 | -232.1 |
| 8 | -213.5 | -265.4 | -240.6 | -218.3 | -214.2 | -211.4 |
| 9 | -191.6 | -255.5 | -233.1 | -201.1 | -195.7 | -191.7 |
| 10 | -172.7 | -243.1 | -230.5 | -187.1 | -180.3 | -174.7 |
| 11 | -156.7 | -226.5 | -232.3 | -176.2 | -168.1 | -160.6 |

*(Continued)*

| Table 3 (Concluded) | | | | | | |
|---|---|---|---|---|---|---|
| Point | T.O.E. | MDC1 | MDC2 | MDC3 | MDC4 | MDC5 |
| | | | $\tau_{xy}$ | | | |
| 1 | 1000 | 898.2 | 892.8 | 895.2 | 893.7 | 894.2 |
| 2 | 742.9 | 754.9 | 743.4 | 749.3 | 745.9 | 747.2 |
| 3 | 493.2 | 514.2 | 495.7 | 507.9 | 501.8 | 504.4 |
| 4 | 321.4 | 343.2 | 322.9 | 342.1 | 333.9 | 337.9 |
| 5 | 251.8 | 258.7 | 241.5 | 268.4 | 258.8 | 264.5 |
| 6 | 225.1 | 209.4 | 200.0 | 235.2 | 224.8 | 232.2 |
| 7 | 206.3 | 166.5 | 168.8 | 212.6 | 202.1 | 211.4 |
| 8 | 188.9 | 122.6 | 139.9 | 192.2 | 182.2 | 193.6 |
| 9 | 172.8 | 78.3 | 112.5 | 172.7 | 163.7 | 177.3 |
| 10 | 158.4 | 36.2 | 86.9 | 153.8 | 146.5 | 162.3 |
| 11 | 145.7 | 10.3 | 63.9 | 135.6 | 130.4 | 148.6 |

**Table 4**
**Tabulation of Finite Element and Closed Form Stress Results for Antisymmetric Normal Pressure**

| Point | T.O.E. | MDB1 | MDB2 | MDB3 | MDB4 | MDB5 |
|---|---|---|---|---|---|---|
| | | | $\sigma_{xx}$ | | | |
| 1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 2 | -133.0 | -160.6 | -171.6 | -172.4 | -173.8 | -179.0 |
| 3 | -20.3 | 6.1 | -11.9 | -12.8 | -15.3 | -15.7 |
| 4 | 59.2 | 71.9 | 48.9 | 48.6 | 45.3 | 44.8 |
| 5 | 63.9 | 84.8 | 57.9 | 58.7 | 54.7 | 54.3 |
| 6 | 43.4 | 77.2 | 47.9 | 49.9 | 45.3 | 45.0 |
| 7 | 26.5 | 64.4 | 34.4 | 37.9 | 32.8 | 32.6 |
| 8 | 16.2 | 51.5 | 23.7 | 28.4 | 22.9 | 22.9 |
| 9 | 10.2 | 38.0 | 16.6 | 22.1 | 16.2 | 16.6 |
| 10 | 6.65 | 23.6 | 12.5 | 18.0 | 11.9 | 12.5 |
| 11 | 4.49 | 7.5 | 10.7 | 15.4 | 9.2 | 10.0 |

*(Continued)*

| Table 4 (Concluded) | | | | | | |
|---|---|---|---|---|---|---|
| Point | T.O.E. | MDB1 | MDB2 | MDB3 | MDB4 | MDB5 |
| | | | $\sigma_{yy}$ | | | |
| 1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 2 | -816.2 | -772.9 | -772.2 | -772.2 | -772.0 | -772.2 |
| 3 | -782.6 | -763.5 | -760.5 | -760.9 | -760.3 | -760.3 |
| 4 | -661.9 | -670.2 | -662.7 | 662.3 | -662.1 | -662.0 |
| 5 | -486.2 | -503.9 | -439.6 | -488.7 | 488.1 | -488.1 |
| 6 | -338.6 | -363.1 | -340.8 | -339.1 | -338.1 | -337.9 |
| 7 | -239.3 | -272.6 | -242.7 | -239.7 | 238.1 | -238.1 |
| 8 | -175.2 | -216.2 | -181.8 | -176.7 | -174.4 | -174.0 |
| 9 | -132.9 | -177.5 | -143.9 | -135.9 | -132.8 | -132.3 |
| 10 | -104.1 | -146.0 | -120.5 | -108.5 | 104.6 | -103.9 |
| 11 | -83.7 | -116.6 | -106.5 | -89.7 | -84.9 | -83.9 |
| | | | $\tau_{yy}$ | | | |
| 1 | -500.0 | -410.4 | -415.9 | -416.3 | -416.9 | -417.1 |
| 2 | -291.0 | -268.0 | -280.1 | -281.1 | -282.5 | -283.8 |
| 3 | -196.3 | -168.7 | -189.5 | -190.9 | -193.8 | -194.2 |
| 4 | -58.7 | -29.1 | -54.7 | 56.2 | -60.1 | -60.7 |
| 5 | 33.8 | 59.8 | 33.5 | 32.4 | 27.8 | 27.1 |
| 6 | 63.7 | 87.9 | 65.0 | 64.9 | 59.7 | 58.9 |
| 7 | 64.4 | 83.6 | 68.0 | 69.5 | 63.9 | 63.2 |
| 8 | 56.8 | 65.5 | 60.8 | 64.4 | 58.8 | 58.2 |
| 9 | 48.2 | 42.5 | 50.7 | 57.1 | 51.6 | 51.1 |
| 10 | 40.6 | 19.4 | 40.3 | 49.8 | 44.7 | 44.5 |
| 11 | 34.3 | 2.1 | 30.5 | 43.1 | 38.1 | 38.7 |

**Table 5**
**Percentage of Error in $\sigma_{xx}$ Stress**

| Node | Stresses for Indicated Load Cases | | | | | |
|---|---|---|---|---|---|---|
| | 1 | | 2 | | 3 | |
| | Model 3 | Model 4 | Model 3 | Model 4 | Model 3 | Model 4 |
| 1 | 11.2 | 7.1 | 0.0 | 0.0 | 0.0 | 0.0 |
| 3 | 27.6 | 21.7 | 4.9 | 3.5 | 36.9 | 24.6 |
| 5 | 33.6 | 25.2 | 3.7 | 1.6 | 8.1 | 14.3 |
| 7 | 35.7 | 28.4 | 0.9 | 1.4 | 43.0 | 11.4 |
| 9 | 28.9 | 22.9 | 5.5 | 5.5 | 117.0 | 58.8 |
| 11 | 17.7 | 13.7 | 9.6 | 5.9 | 242.0 | 107.0 |

**Table 6**
**Foundation Size Models**

| Size Model | Depth[1] | Width[1] | No. of Nodes[2] | No. of Elements[2] | Size Ratio[3] |
|---|---|---|---|---|---|
| 1 | 1.5 BW | 3 BW | 492 | 112 | 1.00 |
| 2 | 2.0 BW | 4 BW | 626 | 144 | 1.78 |
| 3 | 3.0 BW | 5 BW | 850 | 198 | 3.33 |

[1] Depth and width in terms of BW of dam.
[2] The numbers of nodes and elements do not include the dam model.
[3] Size ratio with respect to (w.r.t.) Model 1, based on ratios of foundation model area.

## Table 7
## Effect of Model Size on Vertical Stresses (Syy) (Stresses in psi)

| Node[2] | Foundation Size Model[1] 1 (1.5 BW x 3 BW) | 2 (2 BW x 4 BW) | 3 (3 BW x 5 BW) |
|---|---|---|---|
| 629 | 26.32 | 22.85 | 20.00 |
| 630 | -58.82 | -59.51 | -60.03 |
| 631 | -91.41 | -91.03 | -90.62 |
| 632 | -98.06 | -97.53 | -97.05 |
| 633 | -96.73 | -96.32 | -96.01 |
| 634 | -100.99 | -100.48 | -100.12 |
| 635 | -104.83 | -104.24 | -103.82 |
| 636 | -106.62 | -106.10 | -105.75 |
| 637 | -107.33 | -106.94 | -106.70 |
| 638 | -101.00 | -100.70 | -100.55 |
| 639 | -96.27 | -96.29 | -96.39 |
| 640 | -91.88 | -92.49 | -92.90 |
| 641 | -116.00 | -118.34 | -119.72 |
| 661 | -39.48 | -40.44 | -40.95 |
| 662 | -60.53 | -60.97 | -61.29 |
| 663 | -65.85 | -66.20 | -66.51 |
| 664 | -80.30 | -80.21 | -80.16 |
| 665 | -88.04 | -87.74 | -87.52 |
| 666 | -92.33 | -91.95 | -91.69 |
| 667 | -95.50 | -95.09 | -94.82 |
| 668 | -97.86 | -97.43 | -97.14 |
| 669 | -99.75 | -99.37 | -99.11 |
| 670 | -101.05 | -100.84 | -100.70 |
| 671 | -100.11 | -100.19 | -100.25 |
| 672 | -92.34 | -92.72 | -92.97 |
| 673 | -103.20 | -104.70 | -105.66 |

[1] Er/Ec = 1.00 for all models.
[2] See Figure 25.

**Table 8**
**Effect of Model Size on Horizontal Stresses (Sxx)**
**(Stresses in psi)**

| Node[2] | Foundation Size Model[1] | | |
|---|---|---|---|
| | 1 (1.5 BW x 3 BW) | 2 (2 BW x 4 BW) | 3 (3 BW x 5 BW) |
| 629 | 51.63 | 46.80 | 41.84 |
| 630 | 14.52 | 11.20 | 7.74 |
| 631 | -11.30 | -13.52 | -15.80 |
| 632 | -21.29 | -23.14 | -25.03 |
| 633 | -25.91 | -27.57 | -29.20 |
| 634 | -29.72 | -31.31 | -32.78 |
| 635 | -34.68 | -36.14 | -37.40 |
| 636 | -40.89 | -42.33 | -43.45 |
| 637 | -45.85 | -47.26 | -48.24 |
| 638 | -53.46 | -54.91 | -55.79 |
| 639 | -63.64 | -65.22 | -66.07 |
| 640 | -102.35 | -104.85 | -105.99 |
| 641 | -147.23 | -150.93 | -152.54 |
| 661 | -73.32 | -73.12 | -72.87 |
| 662 | -46.17 | -47.00 | -47.80 |
| 663 | -23.69 | -25.33 | -26.93 |
| 664 | -33.04 | -34.35 | -35.60 |
| 665 | -32.06 | -33.42 | -34.71 |
| 666 | -35.10 | -36.42 | -37.60 |
| 667 | -38.15 | -39.43 | -40.52 |
| 668 | -42.33 | -43.58 | -44.57 |
| 669 | -45.63 | -46.86 | -47.77 |
| 670 | -52.31 | -53.54 | -54.38 |
| 671 | -63.02 | -64.42 | -65.26 |
| 672 | -66.72 | -67.90 | -68.62 |
| 673 | -66.72 | -67.90 | -68.62 |

[1] Er/Ec = 1.00 for all models.
[2] See Figure 25.

**Table 9**
**Effect of Model Size on Shear Stresses (Sxy) (Stresses in psi)**

| Node[2] | Foundation Size Model[1] | | |
|---|---|---|---|
| | 1 (1.5 BW x 3 BW) | 2 (2 BW x 4 BW) | 3 (3 BW x 5 BW) |
| 629 | 87.21 | 83.80 | 80.48 |
| 630 | 44.06 | 42.53 | 41.11 |
| 631 | 19.86 | 19.46 | 19.18 |
| 632 | 22.52 | 22.27 | 22.19 |
| 633 | 28.20 | 27.95 | 27.89 |
| 634 | 29.71 | 29.66 | 29.77 |
| 635 | 31.96 | 32.06 | 32.31 |
| 636 | 36.99 | 37.23 | 37.58 |
| 637 | 43.19 | 43.57 | 43.98 |
| 638 | 46.77 | 47.19 | 47.62 |
| 639 | 48.87 | 49.31 | 49.71 |
| 640 | 75.42 | 76.67 | 77.44 |
| 641 | 117.73 | 102.03 | 121.65 |
| 661 | 5.15 | 4.78 | 4.50 |
| 662 | 20.36 | 19.69 | 19.13 |
| 663 | 36.27 | 35.23 | 34.30 |
| 664 | 29.65 | 29.10 | 28.66 |
| 665 | 30.42 | 30.08 | 29.86 |
| 666 | 32.17 | 32.02 | 31.98 |
| 667 | 35.19 | 35.19 | 35.27 |
| 668 | 39.24 | 39.38 | 39.57 |
| 669 | 44.27 | 44.54 | 44.81 |
| 670 | 52.51 | 52.96 | 53.32 |
| 671 | 61.49 | 62.13 | 62.56 |
| 672 | 69.56 | 70.37 | 70.92 |
| 673 | 85.18 | 86.41 | 87.20 |

[1] Er/Ec = 1.00 for all models.
[2] See Figure 25.

## Table 10
## Effect of Model Size Upon Vertical and Horizontal Displacements

| Node[2] | X-Displacements (in.) Foundation Size Model[1] | | | Y-Displacements (in.) Foundation Size Model[1] | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 1 | 2 | 3 |
| 629 | 0.01572 | 0.01679 | 0.01406 | -0.03902 | -0.05184 | -0.07437 |
| 630 | 0.01700 | 0.01794 | 0.01508 | -0.04185 | -0.05434 | -0.07632 |
| 631 | 0.01774 | 0.01858 | 0.01562 | -0.04405 | -0.05621 | -0.07772 |
| 632 | 0.01796 | 0.01873 | 0.01570 | -0.04557 | -0.05743 | -0.07846 |
| 633 | 0.01796 | 0.01867 | -0.01557 | -0.04656 | -0.05811 | -0.07867 |
| 634 | 0.01788 | 0.01852 | 0.01537 | -0.04704 | -0.05827 | -0.07838 |
| 635 | 0.01765 | 0.01824 | 0.01504 | -0.04698 | -0.05790 | -0.07754 |
| 636 | 0.01727 | 0.01780 | 0.01455 | -0.04636 | -0.05696 | -0.07614 |
| 637 | 0.01667 | 0.01715 | 0.01387 | -0.04510 | -0.05538 | -0.07409 |
| 638 | 0.01588 | 0.01631 | 0.01299 | -0.04316 | -0.05312 | -0.07136 |
| 639 | 0.01473 | 0.01511 | 0.01176 | -0.04050 | -0.05012 | -0.06789 |
| 640 | 0.01267 | 0.01298 | 0.00960 | -0.03686 | -0.04613 | -0.06342 |
| 641 | 0.00930 | 0.00940 | 0.00610 | -0.03128 | -0.04016 | -0.05694 |
| 661 | 0.02392 | 0.02446 | 0.02105 | -0.03925 | -0.05210 | -0.07459 |
| 662 | 0.02242 | 0.02295 | 0.01954 | -0.04380 | -0.05628 | -0.07825 |
| 663 | 0.02194 | 0.02243 | 0.01898 | -0.04620 | -0.05837 | -0.07990 |
| 664 | 0.02148 | 0.02193 | 0.01844 | -0.04802 | -0.05990 | -0.08098 |
| 665 | 0.02112 | 0.02152 | 0.01799 | -0.04917 | -0.06076 | -0.08140 |
| 666 | 0.02077 | 0.02112 | 0.01755 | -0.04982 | -0.06112 | -0.08134 |
| 667 | 0.02035 | 0.02067 | 0.01706 | -0.05000 | -0.06101 | -0.08079 |
| 668 | 0.01984 | 0.02011 | 0.01616 | -0.04967 | -0.06039 | -0.07975 |
| 669 | 0.01921 | 0.01944 | 0.01576 | -0.04879 | -0.05921 | -0.07814 |
| 670 | 0.01846 | 0.01865 | 0.01494 | -0.04728 | -0.05711 | -0.07591 |
| 671 | 0.01719 | 0.01761 | 0.01390 | -0.04508 | -0.05490 | -0.07297 |
| 672 | 0.01613 | 0.01623 | 0.01247 | -0.04208 | -0.05160 | -0.06924 |
| 673 | 0.01471 | 0.01479 | 0.01101 | -0.03842 | -0.04765 | -0.06485 |

[1] Er/Ec = 1.00 for all models.
[2] See Figure 25.

## Table 11
## Foundation Material Properties

| Property Model | Poisson's Ratio | Modulus of Elasticity | | Er/Ec |
|---|---|---|---|---|
| | | Rock (Er) x $10^6$ psi | Concrete (Ec) x $10^6$ psi | |
| A | 0.20 | 12.0 | 4.0 | 3.0 |
| B | 0.20 | 7.0 | 4.00 | 1.75 |
| C | 0.20 | 4.0 | 4.0 | 1.00 |
| D | 0.20 | 1.0 | 4.0 | 0.25 |
| E | 0.20 | 0.20 | 4.0 | 0.05 |
| F | 0.20 | ∞ | 4.0 | ∞ |

## Table 12
## GTSTRUDL Computer Runs

| Run | Model[1] | Er/Ec[2] |
|---|---|---|
| 1 | 3A | 3.00 |
| 2 | 3B | 1.75 |
| 3 | 3D | 0.25 |
| 4 | 3E | 0.05 |
| 5 | F | ∞ |

[1] Foundation modeled with infinite stiffness fixed supports at base of dam.
[2] See Table 11 for definition.

**Table 13**
**Effect of Foundation Stiffness on Vertical (Syy) Stresses (Stresses in psi)**

| Node[1] | Er/Ec Ratio | | | | | |
|---|---|---|---|---|---|---|
| | 0.05 | 0.25 | 1.00 | 1.75 | 3.00 | ∞ |
| 897 | -196.25 | -50.83 | +56.91 | +84.29 | +101.93 | +127.66 |
| 899 | -75.94 | -84.01 | -81.77 | -77.36 | -72.20 | -55.43 |
| 901 | -80.73 | -82.05 | -83.16 | -83.49 | -83.68 | 83.70 |
| 903 | -78.62 | -85.27 | -93.42 | -96.44 | 98.88 | -104.56 |
| 905 | -78.21 | -86.57 | -97.80 | -102.35 | -106.20 | -115.71 |
| 907 | -79.32 | -90.20 | -103.97 | -109.57 | -114.36 | -126.31 |
| 909 | -83.64 | -94.11 | -105.06 | -109.32 | -112.91 | -121.63 |
| 911 | -83.60 | [illegible] | -101.92 | -104.55 | -106.59 | -111.29 |
| 913 | -102.30 | -103.21 | -98.93 | -97.60 | -96.60 | -94.76 |
| 915 | -84.00 | -84.97 | -85.32 | -83.75 | -81.27 | -72.76 |
| 917 | -347.48 | -231.01 | -128.47 | -96.89 | -74.55 | -36.86 |
| 941 | -220.94 | -122.54 | -53.38 | -35.11 | -22.26 | -0.31 |
| 943 | -74.15 | -62.82 | -47.44 | -41.71 | -37.17 | -27.57 |
| 945 | -65.54 | -70.80 | -72.68 | -72.33 | -71.69 | -69.09 |
| 947 | -65.11 | -72.87 | -80.59 | -83.06 | -84.91 | -88.53 |
| 949 | -65.79 | -75.59 | -86.85 | -90.89 | -94.11 | -99.15 |
| 951 | -68.89 | -81.03 | -94.95 | -100.11 | -104.32 | -113.88 |
| 953 | -76.32 | -88.52 | -99.75 | -103.64 | -106.77 | -113.70 |
| 955 | -83.00 | -93.37 | -99.96 | -101.95 | -103.50 | -106.85 |
| 957 | -90.27 | -97.54 | -97.38 | -96.55 | -95.71 | -93.71 |
| 959 | -132.36 | -117.83 | -96.62 | -89.66 | -84.37 | -73.93 |
| 961 | -246.37 | -153.97 | -100.40 | -84.56 | -72.64 | -49.76 |

*(Continued)*

[1] See Figure 32.

## Table 13 (Concluded)

| Node | Er/Ec Ratio | | | | | |
|---|---|---|---|---|---|---|
| | 0.05 | 0.25 | 1.00 | 1.75 | 3.00 | ∞ |
| 1250 | -48.40 | -48.68 | -48.90 | -48.98 | -49.03 | -49.22 |
| 1252 | -45.12 | -45.14 | -45.18 | -45.19 | -45.20 | -45.28 |
| 1254 | -41.53 | -41.44 | -41.37 | -41.35 | -41.33 | -41.29 |
| 1256 | -36.15 | -36.10 | -36.03 | -36.00 | -35.98 | -35.78 |
| 1258 | -35.36 | -35.40 | -35.43 | -35.44 | -35.45 | -35.24 |
| 1260 | -35.94 | -36.17 | -36.43 | -36.53 | -36.61 | -36.48 |
| 1262 | -47.32 | -47.47 | -47.60 | -47.63 | -47.66 | -47.78 |
| 1264 | -45.22 | -45.30 | -45.36 | -45.38 | -45.40 | -45.47 |
| 1266 | -43.08 | -43.08 | -43.10 | -43.10 | -43.11 | -43.15 |
| 1268 | -40.95 | -40.90 | -40.87 | -40.86 | -40.85 | -40.85 |
| 1270 | -37.92 | -37.82 | -37.74 | -37.71 | | -37.63 |

## Table 14
## Effect of Foundation Stiffness on Horizontal (Sxx) Stresses (Stresses in psi)

| Node[1] | Er/Ec Ratio | | | | | |
|---|---|---|---|---|---|---|
| | 0.05 | 0.25 | 1.00 | 1.75 | 3.00 | ∞ |
| 897 | 114.50 | 73.59 | 62.55 | 57.69 | 51.87 | 31.91 |
| 899 | 87.03 | 29.27 | 4.83 | 0.13 | -3.57 | -13.86 |
| 901 | 34.08 | 0.17 | -16.52 | -18.57 | -19.47 | -20.92 |
| 903 | 26.45 | -5.20 | -23.70 | -26.43 | -27.34 | -26.14 |
| 905 | 23.49 | -9.09 | -28.66 | -31.36 | -31.97 | -28.93 |
| 907 | 25.06 | -16.41 | -37.52 | -39.24 | -38.61 | -31.58 |
| 909 | 24.77 | -31.24 | -48.39 | -46.67 | -43.16 | -30.41 |
| 911 | 17.97 | -47.07 | -56.67 | -51.29 | -45.07 | -27.82 |
| 913 | 1.53 | -75.35 | -69.61 | -58.07 | -47.51 | -23.69 |
| 915 | -50.12 | -137.38 | -94.81 | -70.67 | -51.85 | -18.19 |
| 917 | -722.18 | -462.15 | -176.77 | -106.03 | -163.89 | -9.22 |

*(Continued)*

[1] See Figure 32.

| Table 14 (Concluded) | | | | | | |
|---|---|---|---|---|---|---|
| Node | Er/Ec Ratio | | | | | |
| | 0.05 | 0.25 | 1.00 | 1.75 | 3.00 | ∞ |
| 941 | -92.56 | -83.28 | -79.82 | -78.64 | -78.28 | -77.97 |
| 943 | -54.35 | -45.53 | -37.70 | -35.96 | -35.17 | -36.17 |
| 945 | -23.68 | -32.81 | -34.49 | -33.62 | -32.64 | -30.60 |
| 947 | -13.44 | -28.42 | -33.64 | -33.14 | -32.08 | -28.37 |
| 949 | -9.92 | -27.95 | -35.17 | -34.79 | -33.52 | -28.20 |
| 951 | -11.33 | -33.32 | -40.50 | -39.19 | -36.86 | -28.15 |
| 953 | -25.57 | -47.27 | -48.47 | -44.55 | -40.18 | -27.43 |
| 955 | -42.67 | -59.72 | -54.19 | -48.11 | -42.25 | -27.16 |
| 957 | -67.14 | -75.17 | -61.14 | -52.63 | -45.16 | -27.68 |
| 959 | -153.92 | -116.34 | -74.69 | -60.48 | -49.84 | -28.94 |
| 961 | -120.89 | -83.04 | -67.00 | -59.25 | -52.22 | -35.51 |
| 1250 | -23.78 | -23.78 | -23.78 | -23.78 | -23.78 | -23.79 |
| 1252 | -23.28 | -23.27 | -23.28 | -23.28 | -23.29 | -23.31 |
| 1254 | -22.89 | -22.83 | -22.81 | -22.82 | -22.83 | -22.86 |
| 1256 | -20.93 | -20.79 | -20.75 | -20.77 | -20.79 | -20.86 |
| 1258 | -18.79 | -18.73 | -18.74 | -18.77 | -18.80 | -18.89 |
| 1260 | -15.79 | -15.90 | -16.02 | -16.06 | -16.10 | -16.20 |
| 1262 | -21.29 | -21.30 | -21.30 | -21.31 | -21.31 | -21.31 |
| 1264 | -21.03 | -21.04 | -21.05 | -21.05 | -21.06 | -21.07 |
| 1266 | -20.79 | -20.80 | -20.82 | -20.83 | -20.83 | -20.85 |
| 1268 | -20.54 | -20.54 | -20.56 | -20.57 | -20.58 | -20.61 |
| 1270 | -20.03 | -20.02 | -20.04 | -20.06 | | -20.12 |

**Table 15**
**Effect of Foundation Stiffness on Shear (Sxy) Stresses (Stresses in psi)**

| Node[1] | Er/Ec Ratio | | | | | |
|---|---|---|---|---|---|---|
| | 0.05 | 0.25 | 1.00 | 1.75 | 3.00 | ∞ |
| 897 | 28.35 | 70.67 | 100.30 | 103.89 | 103.52 | 92.58 |
| 899 | 48.82 | 27.91 | 24.65 | 28.44 | 33.03 | 67.00 |
| 901 | 28.63 | 23.69 | 25.14 | 28.06 | 31.46 | 42.78 |
| 903 | 24.22 | 22.54 | 25.44 | 28.23 | 31.25 | 40.85 |
| 905 | 22.86 | 22.84 | 26.86 | 29.60 | 32.36 | 40.41 |
| 907 | 23.38 | 26.73 | 32.78 | 35.26 | 37.27 | 41.62 |
| 909 | 28.86 | 35.94 | 42.94 | 44.49 | 45.16 | 44.40 |
| 911 | 33.91 | 43.08 | 49.57 | 50.07 | 49.58 | 45.35 |
| 913 | 50.69 | 57.29 | 57.65 | 55.68 | 53.19 | 44.43 |
| 915 | 28.04 | 51.41 | 60.81 | 58.74 | 54.73 | 40.14 |
| 917 | 415.34 | 271.71 | 138.45 | 97.40 | 69.61 | 26.98 |
| 941 | -40.63 | -23.20 | -12.49 | -9.49 | -7.18 | 2.68 |
| 943 | 10.48 | 20.39 | 33.04 | 37.53 | 40.93 | 47.31 |
| 945 | 24.54 | 23.54 | 29.28 | 32.89 | 36.27 | 45.12 |
| 947 | 23.79 | 23.71 | 28.63 | 31.71 | 34.67 | 42.84 |
| 949 | 22.95 | 24.89 | 29.85 | 32.52 | 35.01 | 41.82 |
| 951 | 24.14 | 30.09 | 35.22 | 36.97 | 38.35 | 41.49 |
| 953 | 34.42 | 42.42 | 45.16 | 45.11 | 44.72 | 42.73 |
| 955 | 48.31 | 54.38 | 52.92 | 51.12 | 49.27 | 43.81 |
| 957 | 70.30 | 70.31 | 62.03 | 57.78 | 53.97 | 44.31 |
| 959 | 127.15 | 101.43 | 75.08 | 65.72 | 58.40 | 43.00 |
| 961 | 191.87 | 114.83 | 79.83 | 69.22 | 60.69 | 41.92 |

*(Continued)*

[1] See Figure 32.

## Table 15 (Concluded)

| Node | Er/Ec Ratio | | | | | |
|---|---|---|---|---|---|---|
| | 0.05 | 0.25 | 1.00 | 1.75 | 3.00 | ∞ |
| 1250 | -4.04 | -4.06 | -4.08 | -4.09 | -4.09 | -4.10 |
| 1252 | 3.59 | 3.55 | 3.49 | 3.47 | 3.45 | 3.36 |
| 1254 | 9.74 | 9.73 | 9.69 | 9.67 | 9.65 | 9.55 |
| 1256 | 18.40 | 18.39 | 18.39 | 18.39 | 18.40 | 18.34 |
| 1258 | 21.39 | 21.39 | 21.43 | 21.46 | 21.48 | 21.45 |
| 1260 | 23.78 | 23.93 | 24.09 | 24.15 | 24.20 | 24.24 |
| 1262 | -2.00 | 2.04 | -2.08 | -2.09 | -2.10 | -2.13 |
| 1264 | 1.59 | 1.53 | 1.47 | 1.45 | 1.43 | 1.37 |
| 1266 | 4.76 | 4.70 | 4.64 | 4.61 | 4.59 | 4.45 |
| 1268 | 7.57 | 7.52 | 7.46 | 7.44 | 7.42 | 7.33 |
| 1270 | 11.12 | 11.09 | 11.05 | 11.04 | | 10.94 |

## Table 16
## Effect of Foundation Stiffness on Horizontal (x) Displacements (Displacements in inches)

| Node[1] | Er/Ec Ratio | | | | | |
|---|---|---|---|---|---|---|
| | 0.05 | 0.25 | 1.00 | 1.75 | 3.00 | ∞ |
| 897 | 0.2421 | 0.0492 | 0.0138 | 0.0083 | 0.0051 | 0 |
| 899 | 0.2472 | 0.0518 | 0.0152 | 0.0094 | 0.0059 | 0 |
| 901 | 0.2495 | 0.0527 | 0.0156 | 0.0097 | 0.0060 | 0 |
| 903 | 0.2412 | 0.0534 | 0.0157 | 0.0097 | 0.0060 | 0 |
| 905 | 0.2528 | 0.0539 | 0.0156 | 0.0095 | 0.0059 | 0 |
| 907 | 0.2557 | 0.0545 | 0.0150 | 0.0089 | 0.0053 | 0 |
| 909 | 0.2588 | 0.0545 | 0.0139 | 0.0079 | 0.0045 | 0 |
| 911 | 0.2603 | 0.0539 | 0.0130 | 0.0071 | 0.0039 | 0 |
| 913 | 0.2612 | 0.0526 | 0.0117 | 0.0061 | 0.0032 | 0 |
| 915 | 0.2615 | 0.0501 | 0.0098 | 0.0047 | 0.0023 | 0 |
| 917 | 0.2500 | 0.0409 | 0.0059 | 0.0024 | 0.0009 | 0 |

*(Continued)*

[1] See Figure 32.

| Table 16 (Concluded) | | | | | | |
|---|---|---|---|---|---|---|
| | Er/Ec Ratio | | | | | |
| Node | 0.05 | 0.25 | 1.00 | 1.75 | 3.00 | ∞ |
| 941 | 0.2327 | 0.0558 | 0.0211 | 0.0154 | 0.0119 | 0.0064 |
| 943 | 0.2316 | 0.0546 | 0.0197 | 0.0141 | 0.0105 | 0.0048 |
| 945 | 0.2309 | 0.0538 | 0.0189 | 0.0132 | 0.0097 | 0.0040 |
| 947 | 0.2308 | 0.0534 | 0.0185 | 0.0128 | 0.0093 | 0.0037 |
| 949 | 0.2310 | 0.0531 | 0.0180 | 0.0124 | 0.0090 | 0.0036 |
| 951 | 0.2313 | 0.0524 | 0.0171 | 0.0115 | 0.0083 | 0.0035 |
| 953 | 0.2313 | 0.0512 | 0.0158 | 0.0105 | 0.0075 | 0.0035 |
| 955 | 0.2309 | 0.0502 | 0.0149 | 0.0098 | 0.0071 | 0.0035 |
| 957 | 0.2297 | 0.0488 | 0.0139 | 0.0090 | 0.0065 | 0.0035 |
| 959 | 0.2277 | 0.0469 | 0.0126 | 0.0080 | 0.0057 | 0.0032 |
| 961 | 0.2243 | 0.0441 | 0.0110 | 0.0067 | 0.0047 | 0.0027 |
| 1250 | 0.0307 | 0.0502 | 0.0466 | 0.0447 | 0.0433 | 0.0402 |
| 1252 | 0.0305 | 0.0500 | 0.0463 | 0.0444 | 0.0430 | 0.0399 |
| 1254 | 0.0302 | 0.0497 | 0.0460 | 0.0442 | 0.0427 | 0.0397 |
| 1256 | 0.0297 | 0.0491 | 0.0454 | 0.0436 | 0.0421 | 0.0391 |
| 1258 | 0.0295 | 0.0489 | 0.0451 | 0.0433 | 0.0419 | 0.0388 |
| 1260 | 0.0293 | 0.0487 | 0.0449 | 0.0431 | 0.0417 | 0.0386 |
| 1262 | 0.0199 | 0.0496 | 0.0476 | 0.0459 | 0.0446 | 0.0416 |
| 1264 | 0.0199 | 0.0495 | 0.0475 | 0.0458 | 0.0444 | 0.0415 |
| 1266 | 0.0198 | 0.0494 | 0.0473 | 0.0457 | 0.0444 | 0.0414 |
| 1268 | 0.0197 | 0.0493 | 0.0472 | 0.0456 | 0.0442 | 0.0413 |
| 1270 | 0.0195 | 0.0492 | 0.0471 | 0.0454 | 0.0441 | 0.0412 |

## Table 17
## Effect of Foundation Stiffness on Vertical (y) Displacements (Displacements in Inches)

| Node[1] | Er/Ec Ratio | | | | | |
|---|---|---|---|---|---|---|
| | 0.05 | 0.25 | 1.00 | 1.75 | 3.00 | ∞ |
| 897 | -1.5715 | -0.3056 | -0.0742 | -0.0419 | -0.0242 | 0 |
| 899 | -1.5683 | -0.3089 | -0.0761 | -0.0432 | -0.0250 | 0 |
| 901 | -1.5393 | -0.3087 | -0.0776 | -0.0444 | -0.0259 | 0 |
| 903 | -1.5165 | -0.3072 | -0.0783 | -0.0451 | -0.0265 | 0 |
| 905 | -1.4921 | -0.3046 | -0.0786 | -0.0455 | -0.0269 | 0 |
| 907 | -1.4391 | -0.2966 | -0.0774 | -0.0451 | -0.0267 | 0 |
| 909 | -1.3792 | -0.2841 | -0.0740 | -0.0430 | -0.0255 | 0 |
| 911 | -1.3452 | -0.2757 | -0.0712 | -0.0413 | -0.0243 | 0 |
| 913 | -1.3071 | -0.2652 | -0.0677 | -0.0390 | -0.0229 | 0 |
| 915 | -1.2626 | -0.2526 | -0.0634 | -0.0362 | -0.0211 | 0 |
| 917 | -1.1991 | -0.2332 | -0.0568 | -0.0321 | -0.0185 | 0 |
| 941 | -1.5782 | -0.3089 | -0.0743 | -0.0412 | -0.0230 | -0.0022 |
| 943 | -1.5623 | -0.3111 | -0.0780 | -0.0448 | -0.0265 | -0.0000 |
| 945 | -1.5432 | -0.3111 | -0.0798 | -0.0467 | -0.0282 | -0.0018 |
| 947 | -1.5222 | -0.3099 | -0.0808 | -0.0477 | -0.0292 | -0.0027 |
| 949 | -1.4998 | -0.3077 | -0.0813 | -0.0483 | -0.0298 | -0.0032 |
| 951 | -1.4516 | -0.3009 | -0.0807 | -0.0483 | -0.0300 | -0.0036 |
| 953 | -1.3978 | -0.2904 | -0.0780 | -0.0468 | -0.0291 | -0.0038 |
| 955 | -1.3679 | -0.2834 | -0.0758 | -0.0453 | -0.0281 | -0.0036 |
| 957 | -1.3352 | -0.2749 | -0.0728 | -0.0433 | -0.0267 | -0.0033 |
| 959 | -1.2986 | -0.2646 | -0.0691 | -0.0108 | -0.0249 | -0.0028 |
| 961 | -1.2566 | -0.2527 | -0.0648 | -0.0378 | -0.0227 | -0.0021 |

*(Continued)*

1 See Figure 32.

| Table 17 (Concluded) | | | | | | |
|---|---|---|---|---|---|---|
| | Er/Ec Ratio | | | | | |
| Node | 0.05 | 0.25 | 1.00 | 1.75 | 3.00 | ∞ |
| 1250 | -1.5837 | -0.3263 | -0.0909 | -0.0572 | -0.0384 | -0.0122 |
| 1252 | -1.5677 | -0.3256 | -0.0926 | -0.0591 | -0.0405 | -0.0145 |
| 1254 | -1.5515 | -0.3216 | -0.0939 | -0.0607 | -0.0423 | -0.0164 |
| 1256 | -1.5182 | -0.3218 | -0.0960 | -0.0634 | -0.0452 | -0.0195 |
| 1258 | -1.5014 | -0.3202 | -0.0967 | -0.0641 | -0.0463 | -0.0208 |
| 1260 | -1.1844 | -0.3185 | -0.0974 | -0.0654 | -0.0474 | -0.0220 |
| 1262 | -1.5799 | -0.3267 | -0.0921 | -0.0584 | -0.0397 | -0.0136 |
| 1264 | -1.5725 | -0.3264 | -0.0928 | -0.0593 | -0.0407 | -0.0145 |
| 1266 | -1.5651 | -0.3260 | -0.0935 | -0.0601 | -0.0514 | -0.0155 |
| 1268 | -1.5576 | -0.3255 | -0.0941 | -0.0608 | -0.0423 | -0.0163 |
| 1270 | -1.5463 | -0.3247 | -0.0949 | -0.0618 | -0.0431 | -0.0175 |

**Table 18**
**Effect of Foundation Stiffness on Relative Horiontal Displacement[1]**

| Node[2] | Relative Displacement w.r.t. Er/Ec = 0.05 | | | | | |
|---|---|---|---|---|---|---|
| | Er/Ec Ratio | | | | | |
| | Er/Ec = 0.05 | 0.25 | 1.00 | 1.75 | 3.00 | ∞ |
| 897 | 0.2421 | -0.1929 | -0.2283 | -0.2334 | -0.2370 | NA[3] |
| 899 | 0.2472 | -0.1954 | -0.2320 | -0.2378 | -0.2413 | NA |
| 901 | 0.2495 | -0.1968 | -0.2339 | -0.2398 | -0.2435 | NA |
| 903 | 0.2412 | -0.1878 | -0.2255 | -0.2315 | -0.2352 | NA |
| 905 | 0.2528 | -0.1999 | -0.2372 | -0.2433 | -0.2469 | NA |
| 907 | 0.2557 | -0.2012 | -0.2407 | -0.2468 | -0.2504 | NA |
| 909 | 0.2588 | -0.2043 | -0.2449 | -0.2509 | -0.2543 | NA |
| 911 | 0.2603 | -0.2064 | -0.2473 | -0.2532 | -0.2564 | NA |
| 913 | 0.2612 | -0.2086 | -0.2495 | -0.2551 | -0.2580 | NA |
| 915 | 0.2615 | -0.2114 | -0.2517 | -0.2568 | -0.2592 | NA |
| 917 | 0.2500 | -0.2091 | -0.2441 | -0.2476 | -0.2491 | NA |

*(Continued)*

[1] All displacement in inches.
[2] See Figure 32.
[3] NA = not applicable since nodes are supported in fixed base case.

## Table 18 (Concluded)

| Node | Relative Displacement w.r.t. Er/Ec = 0.05 | | | | | |
|---|---|---|---|---|---|---|
| | Er/Ec Ratio | | | | | |
| | Er/Ec = 0.05 | 0.25 | 1.00 | 1.75 | 3.00 | ∞ |
| 941 | 0.2327 | -0.1769 | -0.2116 | -0.2173 | -0.2208 | -0.2263 |
| 943 | 0.2326 | -0.1770 | -0.2119 | -0.2175 | -0.2211 | -0.2268 |
| 945 | 0.2309 | -0.1771 | -0.2120 | -0.2177 | -0.2212 | -0.2269 |
| 947 | 0.2308 | -0.1774 | -0.2123 | -0.2180 | -0.2215 | -0.2271 |
| 949 | 0.2310 | -0.1779 | -0.2130 | -0.2186 | -0.2220 | -0.2274 |
| 951 | 0.2313 | -0.1789 | -0.2142 | -0.2198 | -0.2230 | -0.2278 |
| 953 | 0.2313 | -0.1801 | -0.2155 | -0.2208 | -0.2238 | -0.2278 |
| 955 | 0.2309 | -0.1807 | -0.2160 | -0.2211 | -0.2238 | -0.2274 |
| 957 | 0.2297 | -0.1795 | -0.2140 | -0.2189 | -0.2214 | -0.2262 |
| 959 | 0.2277 | -0.1808 | -0.2151 | -0.2197 | -0.2220 | -0.2245 |
| 961 | 0.2243 | -0.1798 | -0.2133 | -0.2176 | -0.2196 | -0.2216 |
| 1250 | 0.0307 | 0.0195 | 0.0159 | 0.0140 | 0.0126 | 0.0095 |
| 1252 | 0.0305 | 0.0195 | 0.0158 | 0.0139 | 0.0125 | 0.0094 |
| 1254 | 0.0302 | 0.-195 | 0.0158 | 0.0140 | 0.0125 | 0.0095 |
| 1256 | 0.0297 | 0.0194 | 0.0157 | 0.0139 | 0.0124 | 0.0094 |
| 1258 | 0.0295 | 0.0194 | 0.0156 | 0.0138 | 0.0124 | 0.0093 |
| 1260 | 0.0293 | 0.0194 | 0.0156 | 0.0138 | 0.0124 | 0.0093 |
| 1262 | 0.0199 | 0.0297 | 0.0277 | 0.0260 | 0.0247 | 0.0217 |
| 1264 | 0.0199 | 0.0296 | 0.0276 | 0.0259 | 0.0245 | 0.0216 |
| 1266 | 0.0198 | 0.0296 | 0.0275 | 0.0259 | 0.0246 | 0.0216 |
| 1268 | 0.0197 | 0.0296 | 0.0215 | 0.0259 | 0.0245 | 0.0216 |
| 1270 | 0.0195 | 0.0297 | 0.0276 | 0.0259 | 0.0246 | 0.0217 |

**Table 19**
**Effect of Foundation Stiffness on Relative Vertical Displacement[1]**

| Node[2] | Relative Displacement w.r.t. Er/Ec = 0.05 | | | | | |
|---|---|---|---|---|---|---|
| | Er/Ec Ratio | | | | | |
| | Er/Ec = 0.05 | 0.25 | 1.00 | 1.75 | 3.00 | ∞ |
| 897 | -0.5715 | 1.2659 | 1.4973 | 1.5296 | 1.5473 | NA[3] |
| 899 | -1.5683 | 1.2594 | 1.4922 | 1.5251 | 1.5433 | NA |
| 901 | -1.5393 | 1.2306 | 1.4617 | 1.4949 | 1.5134 | NA |
| 903 | -1.5165 | 1.2093 | 1.4382 | 1.4714 | 1.4900 | NA |
| 905 | -1.4921 | 1.1875 | 1.4135 | 1.4466 | 1.4652 | NA |
| 907 | -1.4391 | 1.1425 | 1.3617 | 1.3940 | 1.4124 | NA |
| 909 | -1.3791 | 1.0950 | 1.3051 | 1.3361 | 1.3536 | NA |
| 911 | -1.3452 | 1.0695 | 1.2740 | 1.3039 | 1.3209 | NA |
| 913 | -1.3071 | 1.4019 | 1.2394 | 1.2681 | 1.2842 | NA |
| 915 | -1.2626 | 1.0100 | 1.1992 | 1.2264 | 1.2415 | NA |
| 917 | -1.1991 | 0.9659 | 1.1423 | 1.1670 | 1.1806 | NA |
| 941 | -1.5782 | 1.2693 | 1.5039 | 1.5370 | 1.5552 | 1.5760 |
| 943 | -1.5623 | 1.2513 | 1.4843 | 1.5175 | 1.5358 | 1.5623 |
| 945 | -1.5432 | 1.2321 | 1.4634 | 1.4965 | 1.5150 | 1.5414 |
| 947 | -1.5222 | 1.2123 | 1.4414 | 1.4745 | 1.4930 | 1.5195 |
| 949 | -1.4998 | 1.1921 | 1.4185 | 1.4515 | 1.4700 | 1.4966 |
| 951 | -1.4516 | 1.1507 | 1.3709 | 1.4033 | 1.4216 | 1.4480 |
| 953 | -1.3978 | 1.1074 | 1.3198 | 1.3510 | 1.3687 | 1.3940 |
| 955 | -1.3679 | 1.0845 | 1.2921 | 1.3226 | 1.3398 | 1.3643 |
| 957 | -1.3352 | 1.0603 | 1.2624 | 1.2919 | 1.3085 | 1.3319 |
| 959 | -1.2986 | 1.0340 | 1.2295 | 1.2578 | 1.2737 | 1.2958 |
| 961 | -1.2566 | 1.0039 | 1.1918 | 1.2188 | 1.2339 | 1.2545 |

*(Continued)*

[1] All displacements in inches.
[2] See Figure 32.
[3] NA = not applicable since nodes are supports in fixed base case.

| Table 19 (Concluded) | | | | | | |
|---|---|---|---|---|---|---|
| Node | Relative Displacement w.r.t. Er/Ec = 0.05 | | | | | |
| | Er/Ec Ratio | | | | | |
| | Er/Ec = 0.05 | 0.25 | 1.00 | 1.75 | 3.00 | ∞ |
| 1250 | -1.5837 | 1.2574 | 1.4928 | 1.5265 | 1.5453 | 1.5715 |
| 1252 | -1.5677 | 1.2421 | 1.4751 | 1.5086 | 1.5272 | 1.5532 |
| 1254 | -1.5515 | 1.2269 | 1.4576 | 1.4908 | 1.5092 | 1.5351 |
| 1256 | -1.5182 | 1.1964 | 1.4222 | 1.4548 | 1.4730 | 1.4987 |
| 1258 | -1.5014 | 1.1812 | 1.4047 | 1.4370 | 1.4551 | 1.4806 |
| 1260 | -1.4844 | 1.1659 | 1.3870 | 1.4190 | 1.4370 | 1.4624 |
| 1262 | -1.5799 | 1.2532 | 1.4878 | 1.5215 | 1.5402 | 1.5663 |
| 1264 | -1.5725 | 1.2461 | 1.4797 | 1.5132 | 1.5318 | 1.5580 |
| 1266 | -1.5651 | 1.2391 | 1.4716 | 1.5050 | 1.5236 | 1.5496 |
| 1268 | -1.5576 | 1.2321 | 1.4635 | 1.4968 | 1.5153 | 1.5413 |
| 1270 | -1.5463 | 1.2216 | 1.4514 | 1.4845 | 1.5029 | 1.5288 |

# Appendix A
# Data Files

```
STRUDL '6 BASE ELEMENTS,3 BU X 5 BU,ER/EC=1.0'
TYPE PLANE STRAIN
UNITS FT LBS
GENE 993 JOI ID 1 1 X 0 0
CHANGES
JOINT COORDINATES
1 0 0
37 716.25 0
617 0 420.76
653 716.25 420.76
661 287.45 441
673 420.17 441
721 298.33 476.5
733 391.417 475.5
881 298.416 572.5
893 326.749 572.5
921 298.416 589.5
933 315.416 589.5
981 298.416 614.5
993 315.416 614.5
GEN 8 1 37 653 617
XD 18 P 3 3 2 2 1 1 1 1 1 1 1 1 1 1 2 2 3 3
YD 11 P 3 3 3 2 1 1 1 1 1 1 1
GEN 8 661 673 733 721
XD 6 P EQ
YD 3 P EQ
GEN 8 721 733 893 881
XD 6 P EQ
YD 8 P EQ
GEN 8 881 893 933 921
XD 6 P EQ
YD 2 P EQ
GEN 8 921 933 993 981
XD 6 P EQ
YD 3 P EQ
ADDITIONS
GEN 18 ELE ID 1 1 F 1 2 T 3 2 T 59 2 T 57 2 T 8 2 T 39 1 T 58 2 T 38 1
REPEAT 10 ID 18 F 56
GEN 6 ELE ID 205 1 F 661 2 T 663 2 T 683 2 T 681 8 T 662 2 -
T 675 1 T 682 2 T 674 1
REPEAT 15 ID 6 F 20
GENE 6 ELE ID 199 1 F 629 2 T 631 2 T 663 2 T 661 2 T 630 2 -
T 655 1 T 662 2 T 664 1
ELEMENT PROPERTIES
1 TO 380 TYPE 'IPQQ' THICK 1.0
CON E 576000000 1 TO 380
POI .2 ALL
STATUS SUPPORTS 1 TO 37 38 57 94 113 150 169 206 225 262 281 318 337
STATUS SUPPORTS 374 393 430 449 486 505 542 561 598 617 56 112 149 168
STATUS SUPPORTS 205 224 261 280 317 336 373 392 429 448 485 504 541 560
STATUS SUPPORTS 597 616 653
JOINT RELEASES
2 TO 36 FORCE X
38 57 94 113 150 169 206 225 262 281 318 337 374 393 FORCE Y
430 449 486 505 542 561 598 617 56 112 149 168 205 FORCE Y
224 261 280 317 336 373 392 429 448 485 504 541 560 FORCE Y
597 616 653 FORCE Y
LOADING 1
ELEMENT LOADS
283 EDGE FOR EDGE 4 GLO VAR UX 104.21 363.8 624.
277 EDGE FOR EDGE 4 GLO VAR UX 624. 889.2 1154.4
271 EDGE FOR EDGE 4 GLO VAR UX 1154.4 1419.6 1684.8
265 EDGE FOR EDGE 4 GLO VAR UX 1684.8 2062.9 2441.4
259 EDGE FOR EDGE 4 GLO VAR UX 2441.4 2819.8 3198.
253 EDGE FOR EDGE 4 GLO VAR UX 3198. 3576.1 3954.6
247 EDGE FOR EDGE 4 GLO VAR UX 3954.6 4333.1 4711.2
241 EDGE FOR EDGE 4 GLO VAR UX 4711.2 5089.3 5467.8
235 EDGE FOR EDGE 4 GLO VAR UX 5467.8 5846.1 6224.4
229 EDGE FOR EDGE 4 GLO VAR UX 6224.4 6602.7 6981.
223 EDGE FOR EDGE 4 GLO VAR UX 6981. 7359.3 7737.6
217 EDGE FOR EDGE 4 GLO VAR UX 7737.6 8096.4 8455.2
211 EDGE FOR EDGE 4 GLO VAR UX 8455.2 8814. 9172.8
205 EDGE FOR EDGE 4 GLO VAR UX 9172.8 9531.6 9890.4
199 EDGE FOR EDGE 4 GLO VAR UX 9890.4 10249.2 10608.
199 TO 380 BODY FOR GLO BY -150.0
181 TO 198 EDGE FOR EDGE 3 GLO UNIF LY -10608.
UNITS INCHES
STIFFNESS ANALYSIS REDUCE BAND
LIST REACTIONS
LIST DISPLACEMENTS
CALCULATE AVERAGE STRESSES FOR 199 TO 380
CALCULATE AVERAGE STRESSES FOR 1 TO 198
SAVE DIRECT 'MODGP'
FINISH
/
```

```
$TRUDL '10 BASE ELEMENTS,3 BU X 5 BU FOUNDATION ,ER=1.0EC
TYPE PLANE STRAIN
UNITS FT LBS
GENE 1569 JOI ID 1 1 X 0 0
CHANGES
JOINT COORDINATES
1 0 0
45 716.25 0
885 0 429.75
929 716.25 429.75
941 297.45 441
961 420.17 441
1037 298.33 475.5
1057 391.417 475.0
1325 298.416 572.5
1345 326.749 572.5
1421 298.416 589.5
1441 315.416 589.5
1549 298.416 614.5
1569 315.416 614.5
GEN 8 1 45 929 885
XD 22 P 3 3 2 2 1 1 .5 .5 .5 .5 1 1 .5 .5 .5 .5 1 1 2 2 3 3
YD 13 P 2 2 2 2 2 1 1 1 1 1 1 1 1
GEN 8 941 961 1057 1037
XD 10 P 1 1 1 1 2 2 1 1 1 1
YD 3 P EQ
GEN 8 1037 1057 1345 1325
XD 10 P 1 1 1 1 2 2 1 1 1 1
YD 9 P EQ
GEN 8 1325 1345 1441 1421
XD 10 P 1 1 1 1 2 2 1 1 1 1
YD 3 P EQ
GEN 8 1421 1441 1569 1549
XD 10 P 1 1 1 1 2 2 1 1 1 1
YD 4 P EQ
ADDITIONS
GEN 22 ELE ID 1 1 F 1 2 T 3 2 T 71 2 T 69 2 T 2 2 T 47 1 T 70 2 -
T 46 1
REPEAT 12 ID 22 F 68
GEN 10 ELE ID 287 1 F 897 2 T 899 2 T 943 2 T 941 2 T 898 2 -
T 931 1 T 942 2 T 930 1
GEN 10 ELE ID 297 1 F 941 2 T 943 2 T 975 2 T 973 2 T 942 2 -
T 963 1 T 974 2 T 962 1
REPEAT 18 ID 10 F 32
 ELEMENT PROPERTIES
 1 TO 486 TYPE 'IPQQ' THICK 1.0
CON E 576000000 287 TO 486
CON E 144000000 1 TO 286
POI .2 ALL
STATUS SUPPORTS 1 TO 45 68 69 114 113 136 137 181 182 204 205 -
249 250 272 273 317 318 340 341 385 386 408 409 453 454 476 477 521 -
522 544 545 589 590 612 613 657 658 680 681 725 726 748 749 793 794 -
816 817 861 862 884 885 929 46
JOINT RELEASES
2 TO 44 FORCE X
46 68 69 113 114 136 137 181 182 204 205 249 250 -
272 273 317 318 340 341 385 386 408 409 453 454 476 477 521 522 -
544 545 589 590 612 613 657 658 680 681 725 726 748 749 793 794 -
816 817 861 862 884 885 929 FORCE Y
 LOADING 1 'HYDROSTATIC USING EDGE LOADS'
 ELEMENT LOADS
447 EDGE FOR EDGE 4 GLO VAR VX 234. 428. 624.
437 EDGE FOR EDGE 4 GLO VAR VX 624. 800.91 977.81
427 EDGE FOR EDGE 4 GLO VAR VX 977.81 1154.72 1331.62
417 EDGE FOR EDGE 4 GLO VAR VX 1331.62 1508.21 1684.8
407 EDGE FOR EDGE 4 GLO VAR VX 1684.8 2021.14 2357.47
397 EDGE FOR EDGE 4 GLO VAR VX 2357.47 2693.81 3030.14
387 EDGE FOR EDGE 4 GLO VAR VX 3030.14 3366.17 3702.19
377 EDGE FOR EDGE 4 GLO VAR VX 3702.19 4038.53 4374.86
367 EDGE FOR EDGE 4 GLO VAR VX 4374.86 4711.2 5047.54
357 EDGE FOR EDGE 4 GLO VAR VX 5047.54 5383.88 5720.21
347 EDGE FOR EDGE 4 GLO VAR VX 5720.21 6056.24 6392.28
337 EDGE FOR EDGE 4 GLO VAR VX 6392.26 6728.6 7064.93
327 EDGE FOR EDGE 4 GLO VAR VX 7064.93 7401.27 7737.6
317 EDGE FOR EDGE 4 GLO VAR VX 7737.6 8096.4 8455.2
307 EDGE FOR EDGE 4 GLO VAR VX 8455.2 8814.0 9172.8
297 EDGE FOR EDGE 4 GLO VAR VX 9172.8 9531.6 9890.4
287 EDGE FOR EDGE 4 GLO VAR VX 9890.4 10249.2 10608.
 287 TO 486 BODY FORCE GLOBAL BY -160.0
265 TO 278 EDGE FOR EDGE 3 GLO UNIF LY -10608.
PRINT JOINT COORDINATES
UNITS INCHES
STIFFNESS ANALYSIS REDUCE BAND
LIST REACTIONS
LIST SUM REACTIONS
LIST DISPLACEMENTS
CALCULATE AVERAGE STRESSES FOR 287 TO 486
CALCULATE AVERAGE STRESSES FOR 1 TO 286
LIST STRESSES
SAVE DIRECT 'MODBP'
FINISH
/
```

```
STRUDL '10 BASE ELEMENTS,3 BU X 5 BW FOUNDATION ,ER=3.0EC
TYPE PLANE STRAIN
UNITS FT LBS
GENE 1569 JOI ID 1 1 X 0 0,
CHANGES
JOINT COORDINATES
1 0 0
45 716.25 0
885 0 429.75
929 716.25 429.75
941 287.45 441
961 420.17 441
1037 293.33 475.5
1057 391.417 475.0
1325 298.416 572.5
1345 326.749 572.5
1421 298.416 589.5
1441 315.416 589.5
1549 298.416 614.5
1569 315.416 614.5
GEN 8 1 45 929 885
XD 22 P 3 3 2 2 1 1 .5 .5 .5 .5 1 1 .6 .5 .5 .5 1 1 2 2 3 3
YD 13 P 8 2 2 2 2 1 1 1 1 1 1 1 1
GEN 8 941 961 1057 1037
XD 10 P 1 1 1 1 2 2 1 1 1 1
YD 3 P EQ
GEN 8 1037 1057 1345 1325
XD 10 P 1 1 1 1 2 2 1 1 1 1
YD 9 P EQ
GEN 8 1325 1345 1441 1421
XD 10 P 1 1 1 1 2 2 1 1 1 1
YD 3 P EQ
GEN 8 1421 1441 1569 1549
XD 10 P 1 1 1 1 2 2 1 1 1 1
YD 4 P EQ
ADDITIONS
GEN 22 ELE ID 1 1 F 1 2 T 3 2 T 71 2 T 69 2 T 2 2 T 47 1 T 70 2 -
T 46 1
REPEAT 12 ID 22 F 68
GEN 10 ELE ID 287 1 F 897 2 T 899 2 T 943 2 T 941 2 T 898 2 -
T 931 1 T 942 2 T 930 1
GEN 10 ELE ID 297 1 F 941 2 T 943 2 T 976 2 T 973 2 T 942 2 -
T 963 1 T 974 2 T 962 1
REPEAT 18 ID 10 F 32
 ELEMENT PROPERTIES
 1 TO 486 TYPE 'IPQQ' THICK 1.0
CON E 576000000 287 TO 486
CON E 1728000000 1 TO 286
POI .2 ALL
STATUS SUPPORTS 1 TO 45 68 69 114 113 136 137 181 182 204 205 -
249 250 272 273 317 318 340 341 385 386 408 409 453 454 476 477 521 -
522 544 545 589 560 612 613 657 658 680 681 725 726 748 749 793 794 -
816 817 861 862 884 886 929 46
JOINT RELEASES
2 TO 44 FORCE X
46 68 69 113 114 136 137 181 182 204 205 249 260 -
272 273 317 318 340 341 385 386 408 409 453 454 476 477 521 522 -
544 545 589 590 612 613 657 658 680 681 725 726 748 749 793 794 -
816 817 861 862 884 885 929 FORCE Y
 LOADING 1 'HYDROSTATIC USING EDGE LOADS'
 ELEMENT LOADS
447 EDGE FOR EDGE 4 GLO VAR VX 234. 429. 624.
437 EDGE FOR EDGE 4 GLO VAR VX 624. 800.91 977.81
427 EDGE FOR EDGE 4 GLO VAR VX 977.81 1154.72 1331.62
417 EDGE FOR EDGE 4 GLO VAR VX 1331.62 1508.21 1684.8
407 EDGE FOR EDGE 4 GLO VAR VX 1684.8 2021.14 2357.47
397 EDGE FOR EDGE 4 GLO VAR VX 2357.47 2693.81 3030.14
387 EDGE FOR EDGE 4 GLO VAR VX 3030.14 3366.17 3702.19
377 EDGE FOR EDGE 4 GLO VAR VX 3702.19 4038.53 4374.88
367 EDGE FOR EDGE 4 GLO VAR VX 4374.86 4711.2 5047.54
357 EDGE FOR EDGE 4 GLO VAR VX 5047.54 5383.88 5720.21
347 EDGE FOR EDGE 4 GLO VAR VX 5720.21 6056.24 6392.26
337 EDGE FOR EDGE 4 GLO VAR VX 6392.26 6728.6 7064.93
327 EDGE FOR EDGE 4 GLO VAR VX 7064.93 7401.27 7737.6
317 EDGE FOR EDGE 4 GLO VAR VX 7737.6 8096.4 8455.2
307 EDGE FOR EDGE 4 GLO VAR VX 8455.2 8814.0 9172.8
297 EDGE FOR EDGE 4 GLO VAR VX 9172.8 9531.6 9890.4
287 EDGE FOR EDGE 4 GLO VAR VX 9890.4 10249.2 10608.
 287 TO 486 BODY FORCE GLOBAL BY -150.0
265 TO 270 EDGE FOR EDGE 3 GLO UNIF LY -10608.
PRINT JOINT COORDINATES
UNITS INCHES
STIFFNESS ANALYSIS REDUCE BAND
LIST REACTIONS
LIST SUM REACTIONS
LIST DISPLACEMENTS
CALCULATE AVERAGE STRESSES FOR 287 TO 486
CALCULATE AVERAGE STRESSES FOR 1 TO 286
LIST STRESSES
SAVE DIRECT 'MOD11P'
FINISH
/
```

## Model 9

```
STRUDL '10 BASE ELEMENTS,3 BU X 5 BU FOUNDATION ,ER=1.0EC
TYPE PLANE STRAIN
UNITS FT LBS
GENE 1569 JOI ID 1 1 X 0 0.
CHANGES
JOINT COORDINATES
1 0 0
45 716.25 0
885 0 429.75
929 716.25 429.75
941 287.45 441
961 420.17 441
1037 290.33 475.5
1057 391.417 475.0
1325 298.416 572.5
1345 326.749 572.5
1421 298.416 589.5
1441 315.416 589.5
1549 298.416 614.5
1569 315.416 614.5
GEN 8 1 45 929 885
XD 22 P 3 3 2 2 1 1 .5 .5 .5 .5 1 1 .5 .5 .5 .5 1 1 2 8 3 3
YD 13 P 2 2 2 2 2 1 1 1 1 1 1 1 1
GEN 8 941 961 1057 1037
XD 10 P 1 1 1 1 2 2 1 1 1 1
YD 3 P EQ
GEN 8 1037 1057 1345 1325
XD 10 P 1 1 1 1 2 2 1 1 1 1
YD 9 P EQ
GEN 8 1325 1345 1441 1421
XD 10 P 1 1 1 1 2 2 1 1 1 1
YD 3 P EQ
GEN 8 1421 1441 1569 1549
XD 10 P 1 1 1 1 2 2 1 1 1 1
YD 4 P EQ
ADDITIONS
GEM 22 ELE ID 1 1 F 1 2 T 3 2 T 71 2 T 69 2 T 2 2 T 47 1 T 70 2 -
T 46 1
REPEAT 12 ID 22 F 68
GEM 10 ELE ID 287 1 F 897 2 T 899 2 T 943 2 T 941 2 T 898 2 -
T 931 1 T 942 2 T 930 1
GEN 10 ELE ID 297 1 F 941 2 T 943 2 T 975 2 T 973 2 T 942 2 -
T 963 1 T 974 2 T 962 1
REPEAT 18 18 10 F 32
 ELEMENT PROPERTIES
 1 TO 486 TYPE 'IPQQ' THICK 1.0
CON E 676000000 287 TO 486
E 576000000 1 TO 286
POI .2 ALL
STATUS SUPPORTS 1 TO 45 68 69 114 113 136 137 181 182 204 205 -
248 250 272 273 317 318 340 341 385 386 408 409 453 454 476 477 521 -
522 544 545 589 590 612 613 657 658 680 681 725 726 748 749 793 794 -
816 817 861 862 884 885 929 46
JOINT RELEASES
2 TO 44 FORCE X
46 68 69 113 114 136 137 181 182 204 205 249 250 -
272 273 317 318 340 341 385 386 408 409 453 454 476 477 521 522 -
544 545 589 590 612 613 657 658 680 681 725 726 748 749 793 794 -
816 817 861 862 885 884 FORCE Y
 LOADING 1 'HYDHOSTATIC USING EDGE LOADS'
 ELEMENT LOADS
447 EDGE FOR EDGE 4 GLO VAR UX 234. 429. 624.
437 EDGE FOR EDGE 4 GLO VAR UX 624. 800.81 977.81
427 EDGE FOR EDGE 4 GLO VAR UX 977.8; 1154.72 1331.62
417 EDGE FOR EDGE 4 GLO VAR UX 1331.62 1508.21 1684.8
407 EDGE FOR EDGE 4 GLO VAR UX 1684.8 2021.14 2357.47
397 EDGE FOR EDGE 4 GLO VAR UX 2357.47 2693.81 3030.14
387 EDGE FOR EDGE 4 GLO VAR UX 3030.14 3366.17 3702.19
377 EDGE FOR EDGE 4 GLO VAR UX 3702.19 4038.63 4374.86
367 EDGE FOR EDGE 4 GLO VAR UX 4374.86 4711.2 5047.54
357 EDGE FOR EDGE 4 GLO VAR UX 5047.54 5383.88 5720.21
347 EDGE FOR EDGE 4 GLO VAR UX 5720.21 6056.24 6392.26
337 EDGE FOR EDGE 4 GLO VAR UX 6392.26 6728.6 7064.93
327 EDGE FOR EDGE 4 GLO VAR UX 7064.93 7401.27 7737.6
317 EDGE FOR EDGE 4 GLO VAR UX 7737.6 8096.4 8455.2
307 EDGE FOR EDGE 4 GLO VAR UX 8455.2 8814.0 9172.8
297 EDGE FOR EDGE 4 GLO VAR UX 9172.8 9531.6 9890.4
287 EDGE FOR EDGE 4 GLO VAR UX 9890.4 10249.2 10608.
 287 TO 486 BODY FORCE GLOBAL BY -150.0
265 TO 270 EDGE FOR EDGE 3 GLO UNIF LY -10608.
UNITS INCHES
STIFFNESS ANALYSIS REDUCE BAND
LIST REACTIONS
 LIST SUM REACTIONS
LIST DISPLACEMENTS
 CALCULATE AVERAGE STRESSES FOR 287 TO 486
CALCULATE AVERAGE STRESSES FOR 1 TO 286
SAVE DIRECT 'MODDP'
 FINISH
/
```

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**13. ABSTRACT** *(Maximum 200 words)*

This study is a continuation of an on-going project by the Computer-Aided Structural Engineering (CASE) Committee on finite element analysis. This method of analysis, though in use for many years, is becoming more widely acclaimed as a viable method of solution available to engineers for structural analyses.

Phase Ib of this study, discussed herein, describes the use of foundations in finite element modeling using a typical Corps structure, a gravity dam. Included in the report are discussions of the various types of foundation models which can be used in a finite element analysis, the size of the foundation finite element model, the effect of the foundation size used in the analysis on stresses in the structure, and the effect of foundation stiffness on the stresses in the structure.

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3909 Halls Ferry Road, Vicksburg, MS 39180-6199

# WATERWAYS EXPERIMENT STATION REPORTS PUBLISHED UNDER THE COMPUTER-AIDED STRUCTURAL ENGINEERING (CASE) PROJECT

| | Title | Date |
|---|---|---|
| Technical Report K-78-1 | List of Computer Programs for Computer-Aided Structural Engineering | Feb 1978 |
| Instruction Report O-79-2 | User's Guide: Computer Program with Interactive Graphics for Analysis of Plane Frame Structures (CFRAME) | Mar 1979 |
| Technical Report K-80-1 | Survey of Bridge-Oriented Design Software | Jan 1980 |
| Technical Report K-80-2 | Evaluation of Computer Programs for the Design/Analysis of Highway and Railway Bridges | Jan 1980 |
| Instruction Report K-80-1 | User's Guide: Computer Program for Design/Review of Curvilinear Conduits/Culverts (CURCON) | Feb 1980 |
| Instruction Report K-80-3 | A Three-Dimensional Finite Element Data Edit Program | Mar 1980 |
| Instruction Report K-80-4 | A Three-Dimensional Stability Analysis/Design Program (3DSAD) | |
| | Report 1: General Geometry Module | Jun 1980 |
| | Report 3: General Analysis Module (CGAM) | Jun 1982 |
| | Report 4: Special-Purpose Modules for Dams (CDAMS) | Aug 1983 |
| Instruction Report K-80-6 | Basic User's Guide: Computer Program for Design and Analysis of Inverted-T Retaining Walls and Floodwalls (TWDA) | Dec 1980 |
| Instruction Report K-80-7 | User's Reference Manual: Computer Program for Design and Analysis of Inverted-T Retaining Walls and Floodwalls (TWDA) | Dec 1980 |
| Technical Report K-80-4 | Documentation of Finite Element Analyses | |
| | Report 1: Longview Outlet Works Conduit | Dec 1980 |
| | Report 2: Anchored Wall Monolith, Bay Springs Lock | Dec 1980 |
| Technical Report K-80-5 | Basic Pile Group Behavior | Dec 1980 |
| Instruction Report K-81-2 | User's Guide: Computer Program for Design and Analysis of Sheet Pile Walls by Classical Methods (CSHTWAL) | |
| | Report 1: Computational Processes | Feb 1981 |
| | Report 2: Interactive Graphics Options | Mar 1981 |
| Instruction Report K-81-3 | Validation Report: Computer Program for Design and Analysis of Inverted-T Retaining Walls and Floodwalls (TWDA) | Feb 1981 |
| Instruction Report K-81-4 | User's Guide: Computer Program for Design and Analysis of Cast-in-Place Tunnel Linings (NEWTUN) | Mar 1981 |
| Instruction Report K-81-6 | User's Guide: Computer Program for Optimum Nonlinear Dynamic Design of Reinforced Concrete Slabs Under Blast Loading (CBARCS) | Mar 1981 |
| Instruction Report K-81-7 | User's Guide: Computer Program for Design or Investigation of Orthogonal Culverts (CORTCUL) | Mar 1981 |
| Instruction Report K-81-9 | User's Guide: Computer Program for Three-Dimensional Analysis of Building Systems (CTABS80) | Aug 1981 |
| Technical Report K-81-2 | Theoretical Basis for CTABS80: A Computer Program for Three-Dimensional Analysis of Building Systems | Sep 1981 |
| Instruction Report K-82-6 | User's Guide: Computer Program for Analysis of Beam-Column Structures with Nonlinear Supports (CBEAMC) | Jun 1982 |

(Continued)

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| | Title | Date |
|---|---|---|
| Instruction Report K-82-7 | User's Guide: Computer Program for Bearing Capacity Analysis of Shallow Foundations (CBEAR) | Jun 1982 |
| Instruction Report K-83-1 | User's Guide: Computer Program with Interactive Graphics for Analysis of Plane Frame Structures (CFRAME) | Jan 1983 |
| Instruction Report K-83-2 | User's Guide: Computer Program for Generation of Engineering Geometry (SKETCH) | Jun 1983 |
| Instruction Report K-83-5 | User's Guide: Computer Program to Calculate Shear, Moment, and Thrust (CSMT) from Stress Results of a Two-Dimensional Finite Element Analysis | Jul 1983 |
| Technical Report K-83-1 | Basic Pile Group Behavior | Sep 1983 |
| Technical Report K-83-3 | Reference Manual: Computer Graphics Program for Generation of Engineering Geometry (SKETCH) | Sep 1983 |
| Technical Report K-83-4 | Case Study of Six Major General-Purpose Finite Element Programs | Oct 1983 |
| Instruction Report K-84-2 | User's Guide: Computer Program for Optimum Dynamic Design of Nonlinear Metal Plates Under Blast Loading (CSDOOR) | Jan 1984 |
| Instruction Report K-84-7 | User's Guide: Computer Program for Determining Induced Stresses and Consolidation Settlements (CSETT) | Aug 1984 |
| Instruction Report K-84-8 | Seepage Analysis of Confined Flow Problems by the Method of Fragments (CFRAG) | Sep 1984 |
| Instruction Report K-84-11 | User's Guide for Computer Program CGFAG, Concrete General Flexure Analysis with Graphics | Sep 1984 |
| Technical Report K-84-3 | Computer-Aided Drafting and Design for Corps Structural Engineers | Oct 1984 |
| Technical Report ATC-86-5 | Decision Logic Table Formulation of ACI 318-77, Building Code Requirements for Reinforced Concrete for Automated Constraint Processing, Volumes I and II | Jun 1986 |
| Technical Report ITL-87-2 | A Case Committee Study of Finite Element Analysis of Concrete Flat Slabs | Jan 1987 |
| Instruction Report ITL-87-1 | User's Guide: Computer Program for Two-Dimensional Analysis of U-Frame Structures (CUFRAM) | Apr 1987 |
| Instruction Report ITL-87-2 | User's Guide: For Concrete Strength Investigation and Design (CASTR) in Accordance with ACI 318-83 | May 1987 |
| Technical Report ITL-87-6 | Finite-Element Method Package for Solving Steady-State Seepage Problems | May 1987 |
| Instruction Report ITL-87-3 | User's Guide: A Three Dimensional Stability Analysis/Design Program (3DSAD) Module | Jun 1987 |
| | Report 1: Revision 1: General Geometry | Jun 1987 |
| | Report 2: General Loads Module | Sep 1989 |
| | Report 6: Free-Body Module | Sep 1989 |

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# WATERWAYS EXPERIMENT STATION REPORTS PUBLISHED UNDER THE COMPUTER-AIDED STRUCTURAL ENGINEERING (CASE) PROJECT

(Continued)

| | Title | Date |
|---|---|---|
| Instruction Report ITL-87-4 | User's Guide: 2-D Frame Analysis Link Program (LINK2D) | Jun 1987 |
| Technical Report ITL-87-4 | Finite Element Studies of a Horizontally Framed Miter Gate<br>Report 1: Initial and Refined Finite Element Models (Phases A, B, and C), Volumes I and II<br>Report 2: Simplified Frame Model (Phase D)<br>Report 3: Alternate Configuration Miter Gate Finite Element Studies–Open Section<br>Report 4: Alternate Configuration Miter Gate Finite Element Studies–Closed Sections<br>Report 5: Alternate Configuration Miter Gate Finite Element Studies–Additional Closed Sections<br>Report 6: Elastic Buckling of Girders in Horizontally Framed Miter Gates<br>Report 7: Application and Summary | Aug 1987 |
| Instruction Report GL-87-1 | User's Guide: UTEXAS2 Slope-Stability Package; Volume I, User's Manual | Aug 1987 |
| Instruction Report ITL-87-5 | Sliding Stability of Concrete Structures (CSLIDE) | Oct 1987 |
| Instruction Report ITL-87-6 | Criteria Specifications for and Validation of a Computer Program for the Design or Investigation of Horizontally Framed Miter Gates (CMITER) | Dec 1987 |
| Technical Report ITL-87-8 | Procedure for Static Analysis of Gravity Dams Using the Finite Element Method – Phase 1a | Jan 1988 |
| Instruction Report ITL-88-1 | User's Guide: Computer Program for Analysis of Planar Grid Structures (CGRID) | Feb 1988 |
| Technical Report ITL-88-1 | Development of Design Formulas for Ribbed Mat Foundations on Expansive Soils | Apr 1988 |
| Technical Report ITL-88-2 | User's Guide: Pile Group Graphics Display (CPGG) Post-processor to CPGA Program | Apr 1988 |
| Instruction Report ITL-88-2 | User's Guide for Design and Investigation of Horizontally Framed Miter Gates (CMITER) | Jun 1988 |
| Instruction Report ITL-88-4 | User's Guide for Revised Computer Program to Calculate Shear, Moment, and Thrust (CSMT) | Sep 1988 |
| Instruction Report GL-87-1 | User's Guide: UTEXAS2 Slope-Stability Package; Volume II, Theory | Feb 1989 |
| Technical Report ITL-89-3 | User's Guide: Pile Group Analysis (CPGA) Computer Group | Jul 1989 |
| Technical Report ITL-89-4 | CBASIN–Structural Design of Saint Anthony Falls Stilling Basins According to Corps of Engineers Criteria for Hydraulic Structures; Computer Program X0098 | Aug 1989 |

(Continued)

# WATERWAYS EXPERIMENT STATION REPORTS PUBLISHED UNDER THE COMPUTER-AIDED STRUCTURAL ENGINEERING (CASE) PROJECT

(Continued)

| | Title | Date |
|---|---|---|
| Technical Report ITL-89-5 | CCHAN–Structural Design of Rectangular Channels According to Corps of Engineers Criteria for Hydraulic Structures; Computer Program X0097 | Aug 1989 |
| Technical Report ITL-89-6 | The Response-Spectrum Dynamic Analysis of Gravity Dams Using the Finite Element Method; Phase II | Aug 1989 |
| Contract Report ITL-89-1 | State of the Art on Expert Systems Applications in Design, Construction, and Maintenance of Structures | Sep 1989 |
| Instruction Report ITL-90-1 | User's Guide: Computer Program for Design and Analysis of Sheet Pile Walls by Classical Methods (CWALSHT) | Feb 1990 |
| Technical Report ITL-90-3 | Investigation and Design of U-Frame Structures Using Program CUFRBC<br>Volume A: Program Criteria and Documentation<br>Volume B: User's Guide for Basins<br>Volume C: User's Guide for Channels | May 1990 |
| Instruction Report ITL-90-6 | User's Guide: Computer Program for Two-Dimensional Analysis of U-Frame or W-Frame Structures (CWFRAM) | Sep 1990 |
| Instruction Report ITL-90-2 | User's Guide: Pile Group–Concrete Pile Analysis Program (CPGC) Preprocessor to CPGA Program | Jun 1990 |
| Technical Report ITL-91-3 | Application of Finite Element, Grid Generation, and Scientific Visualization Techniques to 2-D and 3-D Seepage and Groundwater Modeling | Sep 1990 |
| Instruction Report ITL-91-1 | User's Guide: Computer Program for Design and Analysis of Sheet-Pile Walls by Classical Methods (CWALSHT) Including Rowe's Moment Reduction | Oct 1991 |
| Instruction Report ITL-87-2 (Revised) | User's Guide for Concrete Strength Investigation and Design (CASTR) in Accordance with ACI 318-89 | Mar 1992 |
| Technical Report ITL-92-2 | Fiinite Element Modeling of Welded Thick Plates for Bonneville Navigation Lock | May 1992 |
| Technical Report ITL-92-4 | Introduction to the Computation of Response Spectrum for Earthquake Loading | Jun 1992 |
| Instruction Report ITL-92-3 | Concept Design Example, Computer Aided Structural Modeling (CASM) | |
| | Report 1: Scheme A | Jun 1992 |
| | Report 2: Scheme B | Jun 1992 |
| | Report 3: Scheme C | Jun 1992 |
| Instruction Report ITL-92-4 | User's Guide: Computer-Aided Structural Modeling (CASM) - Version 3.00 | Apr 1992 |
| Instruction Report ITL-92-5 | Tutorial Guide: Computer-Aided Structural Modeling (CASM) - Version 3.00 | Apr 1992 |

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# WATERWAYS EXPERIMENT STATION REPORTS PUBLISHED UNDER THE COMPUTER-AIDED STRUCTURAL ENGINEERING (CASE) PROJECT

(Concluded)

| | Title | Date |
|---|---|---|
| Contract Report ITL-92-1 | Optimization of Steel Pile Foundations Using Optimality Criteria | Jun 1992 |
| Technical Report ITL-92-7 | Refined Stress Analysis of Melvin Price Locks and Dam | Sep 1992 |
| Contract Report ITL-92-2 | Knowledge-Based Expert System for Selection and Design of Retaining Structures | Sep 1992 |
| Contract Report ITL-92-3 | Evaluation of Thermal and Incremental Construction Effects for Monoliths AL-3 and AL-5 of the Melvin Price Locks and Dam | Sep 1992 |
| Instruction Report GL-87-1 | User's Guide: UTEXAS3 Slope-Stability Package; Volume IV, User's Manual | Nov 1992 |
| Technical Report ITL-92-11 | The Seismic Design of Waterfront Retaining Structures | Nov 1992 |
| Technical Report ITL-92-12 | Computer-Aided, Field-Verified Structural Evaluation | |
| | Report 1: Development of Computer Modeling Techniques for Miter Lock Gates | Nov 1992 |
| | Report 2: Field Test and Analysis Correlation at John Hollis Bankhead Lock and Dam | Dec 1992 |
| | Report 3: Field Test and Analysis Correlation of a Vertically Framed Miter Gate at Emsworth Lock and Dam | Dec 1993 |
| Instruction Report GL-87-1 | User's Guide: UTEXAS3 Slope-Stability Package; Volume III, Example Problems | Dec 1992 |
| Technical Report ITL-93-1 | Theoretical Manual for Analysis of Arch Dams | Jul 1993 |
| Technical Report ITL-93-2 | Steel Structures for Civil Works, General Considerations for Design and Rehabilitation | Aug 1993 |
| Technical Report ITL-93-3 | Soil-Structure Interaction Study of Red River Lock and Dam No. 1 Subjected to Sediment Loading | Sep 1993 |
| Instruction Report ITL-93-3 | User's Manual—ADAP, Graphics-Based Dam Analysis Program | Aug 1993 |
| Instruction Report ITL-93-4 | Load and Resistance Factor Design for Steel Miter Gates | Oct 1993 |
| Technical Report ITL-94-2 | User's Guide for the Incremental Construction, Soil-Structure Interaction Program SOILSTRUCT with Far-Field Boundary Elements | Mar 1994 |
| Instruction Report ITL-94-1 | Tutorial Guide: Computer-Aided Structural Modeling (CASM); Version 5.00 | Apr 1994 |
| Instruction Report ITL-94-2 | User's Guide: Computer-Aided Structural Modeling (CASM); Version 5.00 | Apr 1994 |
| Technical Report ITL-94-4 | Dynamics of Intake Towers and Other MDOF Structures Under Earthquake Loads: A Computer-Aided Approach | Jul 1994 |
| Technical Report ITL-94-5 | Procedure for Static Analysis of Gravity Dams Including Foundation Effects Using the Finite Element Method – Phase 1B | Jul 1994 |